CHALMERS

Life Cycle Assessment of Wood Pellet

Master of Science Thesis in the Master Degree Programme, Environmental Measurements and Assessments

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Preface

I would like to express my gratitude to everyone that helped me during the thesis project.

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Siyu Chen
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Summary

The primary purpose of this project is to assess the environmental impacts associated with the wood pellet production. The study has extended to the entire life cycle of wood pellet, which includes the up- and down-stream processes. Therefore it leaves the Life Cycle Assessment (LCA) the best method to carry out such study. LCA is a popular tool for evaluating environmental impacts of products or services. In this study, the mainstream LCA methodology is adopted, which includes four steps starting from goal and scope definition, life cycle inventory analysis, to life cycle impact assessment, and interpretation. The results of the study will be used for the wood pellet producer to communicate with its customers and also facilitate a better environmental management.

The entire life cycle of wood pellet can be divided into eight main processes. According to the results of inventory analysis, the Silviculture is the most fossil fuel-dependant process, while the Pellet Production is, however, the most energy-intense process. Regarding the emissions, the final Combustion process contributes most to the air emissions, but the Pellet Production has a remarkably high emission of hydrocarbons, which can be explained as incomplete combustion of a mass of biofuel. The resources use, on the other hand, is close related to the consumption of electricity, since the electricity production is included in the system. The process with bigger demand of electricity results in bigger amount of resources use.

When it comes to the characterisation level, the inventory data have been aggregated and translated into real environmental impacts. There are at least six different environmental impacts are possible to be initiated from the wood pellets production. It is noted that the Silviculture and the final Combustion are the least environmental preferable processes, due to the relatively big environmental impacts potential in relation to these two processes.

There are three valuation methods involved in the report to weigh the importance of the environmental impacts against from one to another. The results of the three valuation methods are somehow different, which is, however, only because the methods tend to weight the importance of the environmental impacts from different perspective, and there is no such best weighting method exits.

At last, a sensitivity analysis is given to discuss the hot points in the report, which is about to test the uncertainties of the data. Plus a discussion part is made at the end of the report to discuss the account of carbon dioxide emission in bioenergy system, and a crude comparison of avoided green house gas emission of using different kind of wood energy.

Content

1. Introduction

Worldwide, there is a growing interest in using bioenergy due to the environmental and economic concerns. A number of unique features made wood pellet an ideal biofuel for heating in both small-scale combustion units and large-scale heating plants. Compared with unprocessed biomass (such as straw or wet sawdust), wood pellets have higher density and lower moisture content. Additionally other advantages of wood pellets include a higher effective heating value, uniform shape, easy to be transported and so on.

In Sweden, due to the high environmental taxes in using fossil fuels and the high price of fuel oil, the demand of wood pellets increases dramatically, which makes Sweden become the largest wood pellets user in the world since 2004. About half of the wood pellets are burned in district heating plants, whereas 35% (443000 tons) was used for single house heating (Ståhl 2005).

This life cycle assessment study is initiated by Neova, one of the leading biofuel suppliers in Sweden. The purpose of this study is to investigate the environmental impacts of producing wood pellets, especially the contribution of wood pellets to global warming. The results of study will be used to help communicating with future customers.

2. Background

2.1 Wood pellets

Wood pellet is a kind of processed biomass fuel. Compared with unprocessed biomass, wood pellet fuel offers many advantages. By drying and compressing sawdust to pellets, it gives a higher energy density and better combustion properties. Besides wood pellet usually has rather low moisture content, which makes it more resistant to microbial degeneration during handling and storage, and at the same time avoid an uneven combustion with unnecessary emissions and lower efficiency. It also can be automatically fed into the burners, which saves a lot troubles for using wood pellets.

Even compared with traditional fossil fuels, wood pellets also have many advantages. The most obvious is that wood pellets are a renewable fuel, which is considered to be CO_2 neutral and thus not provide any net contribution to the greenhouse effect. Therefore using wood pellets to replace fossil based fuel has great potential to reduce green house gas (GHG) emission. In addition to its advantages on environment, to the customers the price of wood pellet fuel is cheaper than petroleum oil, due to the environmental tax in Sweden.

However, several small drawbacks of using wood pellets needed to be pointed out. First of all, the fine fraction of wood pellets may disturb the combustion and the feed of the pellets into the burner. Furthermore, wood pellets usually need large storage facilities, regular control and removal of ashes, which are not the case when it comes to fossil fuels.

This LCA study is initiated by Neova, one the leading biofuel supplier in Sweden. The pellets plant, which has been used as the reference plant to collect site-specific data, is located in Vaggeryd.

2.2 Short description of wood pellets production process

The raw materials for producing wood pellets are mostly sawdust and shavings, which are byproducts from sawmills. Therefore from the environmental perspective of view, the location of production site is very important, since it determines if the pellet plant is easy to access to cheap raw material and if big environmental impacts will be caused by the transportation of raw materials and products.

The main steps of producing wood pellets involve the following steps:
- Drying of raw material
- Grinding and comminuting
- Pelleting, i.e., shaping and compression of raw material into fuel pellets
- Cooling

- Screening, i.e., return the fine fractions back to the pelleting process
- Storage of pellets

The production process can be shown in the following figure.

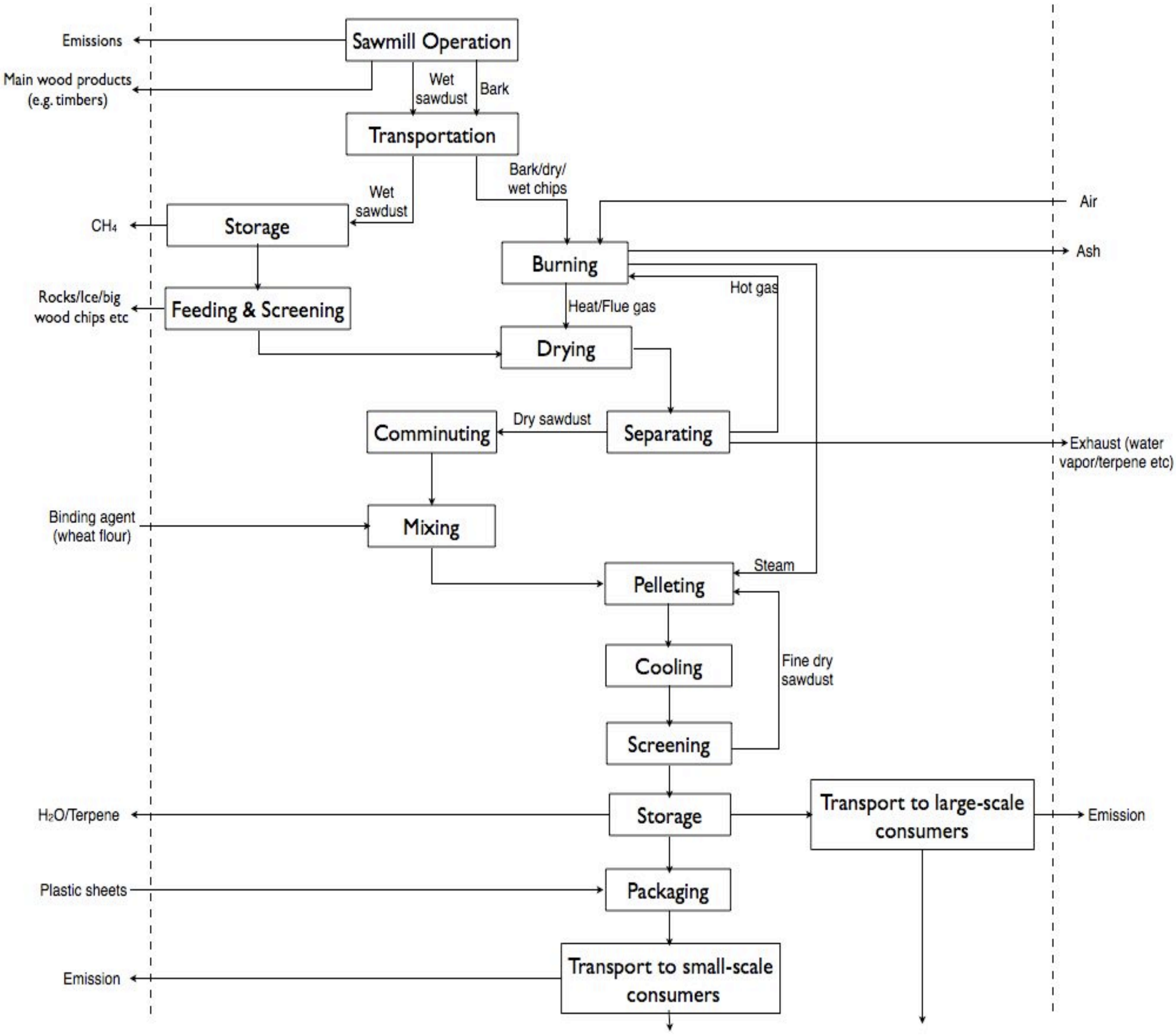

Figure 2.1. Operation processes in pellet plant

The Raw Material

Sawdust of Norway spruce and/or Scots pine is the typical raw material for producing wood pellets in Sweden. Other raw materials, such as hardwood, barks, logging residues, cull tree, energy forest fuel, peat or straw sometimes can be also used or mixed with softwood. Since raw material cost is considered to be the major cost for pellet producers, and the raw material has great influence on the quality of wood pellets, it is important to choose the right raw materials.

Raw material storage

Both the raw material and wood pellets storing are necessary. At the manufacturer's, storage often means indoor or outdoor stack solutions. In most cases the sawdust needs to be stored for months before coming into production process, which helps to provide higher quality pellets compared with pellets made from fresh wood. The raw materials must be correctly stored to avoid, for example, mould growth and anaerobic decomposition with methane emissions. On the contrary, if the treatment is not appropriate, a relatively high temperature within the stacks can be achieved and therefore put the stacks in the risk of self-ignition and loss of volatile substances, i.e., dry matter loss (due to rotting, for instance).

Drying

Drying is usually necessary in producing wood pellets, since dry shavings or dry sawdust is not always the only raw material. The wet raw material typically contains 50-55% of water. If high water content of wood is burned, it leads not only to low energy efficiency but also low combustion temperatures with rather high emissions of hydrocarbons and particles. After drying, the water content of raw materials can be reduced to about 6-12%.

The drying technology used by Neova is a rotary drum dryer with counter-current flow of drying gases. Flue gases are used as a heating medium, which come from burning barks and wood chips. Advantages of this flue gas rotary dryer are relatively cheap and easy to install and run. Drying is one of the major energy consuming processes in pellets production, and is estimated to take about 10%-12% of the heating value of wood pellets (Ståhl, Granström et al. 2004), hence there is a possibility for energy recovery from the gases leaving the dryer.

Grinding

Before compressed into pellets, the dried material is brought to the hammer mill by feeding control. In hammer mill, the sawdust is comminuted into a finer and uniform material, which is necessary to produce pellets with high durability.

Pelleting

Pelleting is the process to compress sawdust into pellets. There the dried and uniformed raw material is transported to the pelleting mill by a screw feeder, which is adjusted to the speed in order to achieve an appropriate and even raw material flow. The material must be mixed with steam in a mixing chamber to make the material hot and soft, before it goes to the dies. This on one hand will increase the moisture content of the pellet, but on the other hand also has a positive effect on the durability of pellet and reduces the wear of the die (Ståhl, Granström et al. 2004).

A ring die, which could be fixed or rotating, with high pressures and temperatures is perhaps the most common technology for pelleting. When the dried sawdust is fed to the die, it will be compressed by the rolls through the die holes, and then cut off by knives. During this process, due the friction that happens when sawdust is pressed through the holes, the temperature rises. This rise of temperature can reach up to 100℃ or even more, which is crucial for the bonding process of pellets, since it has reached the lignin softening temperature (Ståhl, Granström et al. 2004). But if the temperature were lower, more monoterpenes would be kept in the pellet, which helped to increase the durability.

Additives

Sometimes a binding agent is added in order to improve the quality of the pellets. In this case, Neova is using wheat powder, but other additives with advantageous characteristics are often used as well, such as starch and lignin. Nevertheless, it is worthy to point out that it is not always necessary to use additives, since it will probably provide unwanted substances and in consequence to lead a higher ash content and increase the cost of production (Ståhl, Granström et al. 2004).

Cooling

When pellets have been produced, the temperature sometimes can be up to 150°C depending on whether the dried and conditioned raw material were used or not (if not, the temperature often stays around 60-90°C) (Ståhl 2008). The most common cooling technology is simply to use a counter current airflow through the pellet flow to cool the pellets down to ambient temperature. Cooling is necessary since it both transports moisture emitted during the densification step from the hot pellets, and enhances pellet durability and storage stability.

Screening

After cooling, the production process is almost finished. But there is a small part of fine fraction, which does not succeed in compressing into pellets. If this fine fraction is left in the pellets, it will cause many unwanted consequences, for example to cause a high temperature in storage. This is due to the relatively high water absorption capacity of fines which give birth to fungal growth. Besides, the amount of fines in pellets also influences the nitrogen oxide emission from combustion, the more fines the more nitrogen oxides emitted (Olsson 2006). Therefore, after cooling, a screening process is used to bring fines back to the process.

Storage of wood pellets

Before wood pellets can be packed into bags or filled into a bulk transport vehicles, they must be stored in stacks for a period of two or three weeks. The storage enables the wood pellets to get rid of unpleasant smell. Moreover the storage helps the pellets to achieve a better hardness and consistence as well.

2.3 A short description of Life Cycle Assessment

This project is aimed at analyzing the environmental impacts associated with wood pellets production. However, it tends not only to assess the environmental performance of the production process itself, but also to expend the scope to include the up- and downstream processes, which leaves the Life Cycle Assessment (LCA) an ideal method to carry out such study.

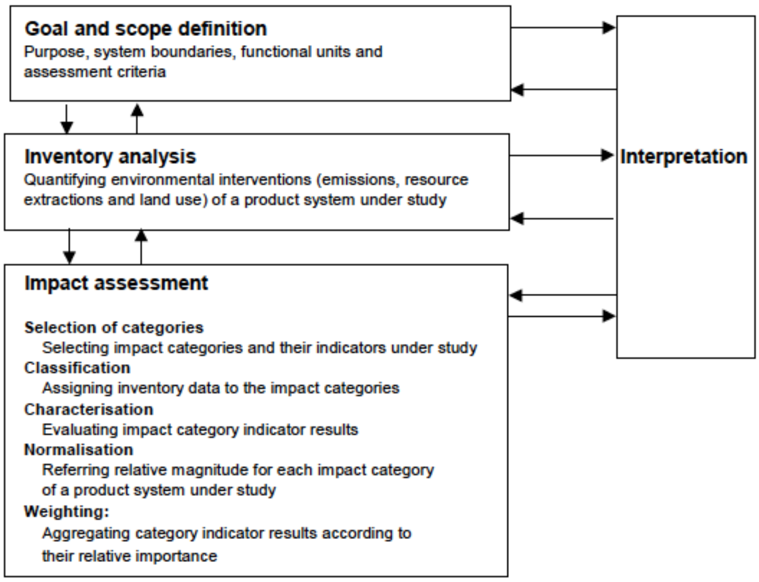

Figure 2.2 Life cycle steps (Seppälä 2003)

LCA is an environmental assessment tool that aimed at analyzing the environmental effects associated with a product or a process or a single activity over the entire course of its life or duration, i.e. from cradle to grave. Such assessment can be achieved by building a system model to quantify the consumption of energy and materials, in the meantime calculating the emissions and wastes released to the environment within the entire life cycle of the system, which usually involved the computation of the effects of extraction of the raw materials, main production processes, transportation, use phase, reuse, recycling and/or final waste disposal process (Rafaschieri, Rapaccini et al. 1999). According to Baumann and Tillman 2004, there are at least four steps for conducting an LCA, as it is shown in figure 2.2.

- Goal and scope definition. To initiate an LCA, the goal must be clearly determined, by stating the intended application and reasons for performing the study. Then according to the goal, the scope is thus to be determined in relation to temporal, geographical and technological coverage (ISO 14040, 14041).

- Inventory analysis. This phase is about to gather all the necessary data (e.g. the resources used, energy use, emissions, and products come out of each process) to generate the mass and energy flow within or between technical system and environment, i.e. to establish a system model based on the requirements of the goal and scope definition (ISO 14041).

- Life cycle impact assessment, which enables to translate the inventory results into environmental impacts. Then to elucidate the magnitude of the potential environmental impact by characterizing the inventory results into real environmental load, for example global warming, acidification, eutrophication and so on (ISO14042).

- Interpretation enables people to understand the result of the study and identify the components that have the most signification environmental impacts (ISO 14043).

3 Goal and scope definition

3.1 Intended application and audience

This life cycle assessment study is initiated by Neova to assess the environmental impacts of producing wood pellets. Therefore the intended application of the study is to gain a solid understanding of the environmental issues associated with the processes of producing wood pellet. The results of the study will be used to communicate with future customers, and in the meantime to assist Neova to facilitate a better environmental management.

The specific questions for conducting this study are:
- What kind of environmental impacts can be associated with wood pellets industry?
- How big environmental impacts be?
- In which part life cycle of this wood pellets production process account for the biggest responsibility for green house gas (GHG) emission?
- Is there anything possibility to reduce the emission?

3.2 Functional unit

Functional unit must reflect the function of the investigated product. As wood pellet, a kind of biofuel, the most obvious function is to supply energy, either heat or electricity. Therefore the functional unit of this LCA study is chosen to be as: ***1GJ (1000 MJ) energy delivered as wood pellets out the pellet plant***.

3.3 Impact categories

According to the Nordic Guidelines on Life-Cycle Assessment, the general impact categories include:

- Resources depletion;
- Human health;
- Ecological consequences.

The impact categories listed above can be further divided into several sub-categories, and will be discussed in later chapter. However, neither the impacts regarding eco-toxicity nor the ones regarding social-economic are included in this standard LCA study.

3.4 Type of LCA

Since the purpose of this study is aimed at investigating the environmental impacts caused by manufacturing wood pellets, and through an earlier stage mapping of the pellet production industry from the point view of LCA, no specific changes of the whole process chin will be made, therefore this is an ***accounting LCA***.

3.5 System boundary

Figure 3.1 is an overview flowchart representing the system that is usually modeled in an LCA study. The technical system is the part that under the interference of human activities, whereas natural system, on the other hand, is generally the environment that is affected by the consequences of human activities.

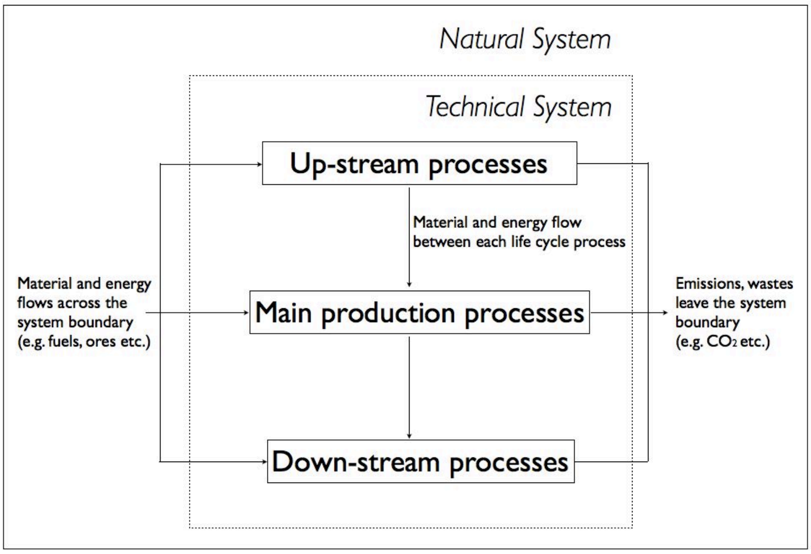

Figure 3.1 Overview flowchart

Come to this project, the system can be decided as following:

3.5.1 Natural system

The definition of natural system boundary is one of the difficulties in LCA study, especially when it comes to the products whose production process involves renewable resource.

- The cradle of wood pellet is the forest, which starts with seedling, and its life cycle ends with dumping the combusted waste-ash in landfills or using them as fertilizers in forests. So forest in this study is included in technical system.
- Water, air, sunlight are not considered to be scarce resources and therefore a part of natural system.

3.5.2 Geographical boundaries

Since Sweden has a big demand for pellet fuel, the wood pellets that Neova produced mainly sold in domestic market. In addition to the market to which the products sell, the raw materials are also supplied by sawmills located in different part of Sweden. Therefore the geographical boundaries of this study can be clearly defined as ***within Sweden***.

3.5.3 Time horizon

The time horizon of LCA study is very much depending on the effectiveness of the collected data. In this course, the intention of the project tends to choose the most lately data, which represents the last a few years, and when the present data is not available, a very small part of old data, which is relatively old and can be traced back to 1990's, is used to even the gap.

3.5.4 Technical system

Boundary within the life cycle

Since electricity is highly refined energy which is different from the primary energy that can be acquired directly from the nature, such as coal, oil and so on, it is reasonable to include the environmental load associated with electricity production in the system, shown in Figure 3.2. In such circumstance, only the fuels used for producing electricity enter the system, electricity is, however, treated as an internal parameter. Therefore the demand of resources as well as the emissions for electricity production will be added to each life cycle process according to the amount of electricity it demands, and hence become a part of the environmental load that the product shares.

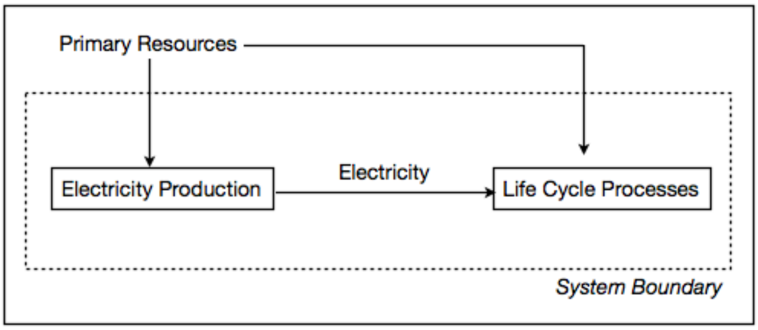

Figure 3.2 Illustration of system boundary of electricity production (Sunér 1996)

Up-streams

The raw material for producing wood pellet is considered to be only sawdust, which is one of the co-products from sawmill where the upstream boarder is the forestry. Especially for the production of electricity, it sometimes depends on mineral resources, for example the uranium ore. Due to lack of information and time pressure, the environmental load in relation to some of the inflows (for example to extract uranium ore), have not been traced back to the cradle.

Down-streams

Although the end of a life cycle is always chosen to dispose the waste at landfills, in this case the only waste needs to be taken care of is the ash resulted from combusting wood pellets. Regarding other wastes come out from each life cycle process, such as building wastes or hazardous wastes etc., due to the vagueness of the date, to find out the specific environmental impacts in relation to these substances are rarely possible. Therefore all these outflows are not followed to the grave.

Cut-off criteria

The environmental impacts associated with the production of capital goods and personnel-related environmental impacts (for example the transportation of labors to the working field) are not counted in.

Allocation

Allocation means to partition the environmental load among the different products and/or among subsequent product systems

It is not uncommon that allocation problems usually occur in forestry-related industry, since various products will be simultaneously produced along with the entire wood operation process. One of the most obvious reasons to initiate this problem is lying in the nature of the main functions of woods: for material use and the use for energy production. Besides the raw materials for producing a variety of wood-related products are originated from forestry, such as paper, particle boards, biofuels etc.. Therefore this multi-function trigged the three generic causes where allocation is an issue:

- Multi-output process, where the material flows of the process and its up-stream processes must be allocated to the various co-products (Jungmeier, Werner et al. 2002). For example: at the sawmill, co-products, such as sawdust, barks, wood chips, are produced with the main products, sawn timber, at the same time.
- Multi-input process, where the emissions and the generated energy must allocated to the various input products or product systems (Jungmeier, Werner et al. 2002). For example: at the CPH, different fractions of waste wood are used for combustion and thus to generate heat or electricity.
- Recycling and reuse, where primary production and final disposal must be allocated to several subsequent product systems (Jungmeier, Werner et al. 2002). For example: wood-made boxes for package use.

In this case, multi-output process is under consideration, since it is estimated that during the sawmill operation, the co-products account for approximately 50% volume of the sawn log, and sawdust, which is one of the co-product from sawmills, is treated as the exclusive raw material for wood pellet production, which makes it a crucial allocation problem for the wood chain.

ISO 14044 made several recommendations for handling LCA allocation problems. The principles are generalized as following:

- Avoid allocation through increasing the details of the system
- Avoid allocation through expanding the system
- Underlying relationship of different products should be established to partition the environmental loads
- Except physical relationship, other relative values could be involved to help building relative relationship and thus help partitioning; such value could be economic value of each product for example.

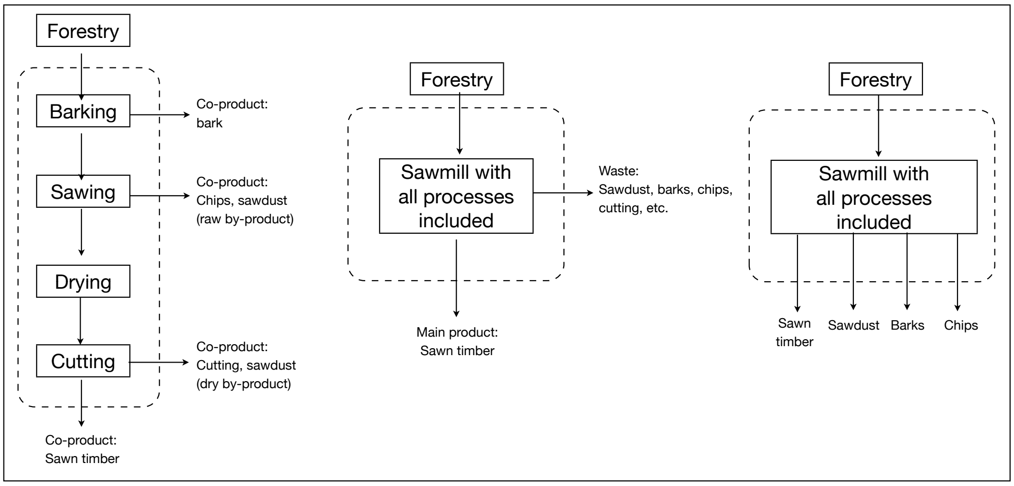

Figure 3.3 Methods for allocation (Jungmeier, Werner et al. 2002)

Jungmeier and Werner (2002) suggest three different approaches to address the allocation of materials and energy input and emissions at a sawmill, which is generally shown in Figure 3.3. For the first method, the underline physical relation is established based on the volumes of different products from sawmill, and therefore all products are considered to be co-products(Jungmeier, Werner et al. 2002). Environmental loads are evenly distributed to each co-product according to their volume content. However, this method to some extent increases the details of the system by dividing the sawmill operation into several separate processes, just in order to avoid some allocations. To be different, in the second method only the main product that is timbers, is considered to be the valuable product, others are all treat as waste (Jungmeier, Werner et al. 2002). Therefore timbers should responsible for all environmental load caused during the sawmill operation process, and other co-products are regarded as free of environmental burden. The third approach for allocation is based on the economic value of each co-product (Jungmeier, Werner et al. 2002). Market prices are collected and used for generate the underline relationship among different co-products to partition the environmental burdens.

However, each approach has its advantage and drawbacks. It is hard to make judgment on which approach is the best. The use of volume or weight as the basis for proceed allocation is always the most common and easiest way of method, since it is not always difficult to measure the volume or the weight of the product, but it also gives birth to a problem that the arbitrariness during the measurement. The second method that treats all the co-products as environmental impacts free is also a very convenient way of dealing with allocation, but it hides the truth that in many cases co-products have great influence on the overall environmental performance of the products, and hence not reasonable to have them omitted. The third method that using market prices of each co-products to generate the underline relationship also has a remarkable disadvantage that the price of the products fluctuates from time to time.

In this study, the economic-oriented way of allocation is adopted.

3.6 Data

Parameters

It is quite common to have many parameters to be involved in a certain LCA study. But since the production of wood pellets is relatively simple and straightforward compared with many other industrial products, whose raw materials are various and manufacturing processes are much more complicated. This study is small enough that only several common parameters were picked up to describe environmental loads.

The parameters used to describe environmental loads can be classified as:

Demand for natural resources: natural gas, coal, oil, copper ore, lead ore, iron ore, bauxite, uranium
Demand for energy resources: diesel, biofuels
Emission to air: CO_2, CO, PM, NO_x, SO_2, CH_4, HC, N_2O
Emission to water: N-tot
Waste: ash, other waste (building waste, hazardous waste etc.)

Data quality

Most of the data were collected at the producing companies, which to a large extent will make the study as objective as possible to reflect the real environmental performance of the product. But since Neova is only able to provide data regarding its production process on the pellet plant, for up- and downstream processes, the project carrier tried to reach the actual suppliers and customers. This works for some processes, but not for all. It is also not possible to make connection with all the suppliers and customers to draw the whole picture, therefore some secondary sources of data is used as backup, which include literature data, journal paper, published LCA report, LCA database etc..

There are many places in the project that need to transform the collected data from one form to another, since it is not often possible to have the data in a form that is exactly the same as what I wanted. For example, in some circumstances, the data on actual energy demand is easy to be found, but the emissions in relation to energy use is not always available, which have to be calculated by using standardized emission factors. Additionally, although it is rare, there exits a small part of data that is blank in any type of sources, then it filled with estimated data.

To summarize, the data sources have been chiefly used in this report include:

- Environmental reports
- Journal paper
- LCA database
- Literature (mainly published LCA-studies)
- Personal interview

3.7 Assumptions and limitations

- For LCAs where the purpose is to improve the environmental performance of a product or to find the best alternative of more than one product with the same function, it might be most relevant to use marginal data for processes such as electricity production and transports, since the improvement or choice will influence the system on the marginal and not the acerage. However, in this study, the data of electricity production is calculated as average data.

-There are four pelleting plants running by Neova, but only the one located at Vaggeryd is taken as reference plant. All the site-specific data are collected from this plant.

-The raw material in producing wood pellets is only fresh sawdust, which requires drying before compressed into pellets. Although a small part of dry sawdust is also used in other plants, it has been excluded from the study.

-Barks is consider as the only fuel in supplying heat for drying, even though a small quantity of chips are also used as fuel for heating as well.

-There is always a gap for data collection. Therefore in this study some assumptions are made in order to precede the study. For example, the environmental data regarding sawmill operation is mainly originated from the environmental declaration of four sawmills located in different part of Sweden. Although there are hundreds of sawmills operating in Sweden at present, it is assumed that the four sawmills are representative.

-Except the site-specific data that collected directly from Neova, other data used in this study generally originated from public LCI database and published scientific reports and papers. Even if it is believed that the collected data quality itself is trustworthy, they are still from secondary data sources that will probably hinder the credence of the entire study.

4 Inventory analysis

Life cycle inventory analysis is about to establish the model to simulate the technical system, and at the same time calculate the mass and energy flow within and between the system boundary. At this phase, an elaborated flowchart will be made first, then data will be collected to calculate the environmental loads in relation to functional unit.

4.1 System description

The entire life cycle of wood pellets can be viewed in figure 4.1. The processes in this system consist of:

• Silviculture
• Round wood transportation
• Sawmill operation
• Raw material transportation
• Pellet production
• Pellet distribution
• Pellet combustion
• Waste management

The data quality is heterogeneous. The data used comes from various sources, which include scientific reports, published LCI data and data from LCI database. The site-specific data is collected at the reference pellet plant, which is one of Neova's four pellet mills, located near the town Vaggyerd west Sweden. The data regarding production process is fairly new, however some data, especially the forestry date, are relatively old.

4.2 Calculation methods

To establish the material and energy flow between each life cycle process and across the system boundary is crucial for the system studied in the inventory part of an LCA. Three main types of calculations need to be done to generate such material and energy flows:

- The mass balance of each process needs to be generated first, and then the material flow between each process and across the system boundary will be calculated with the reference of the functional unit.

- The energy is calculated by counting the energy use of each process of the system respectively, which specified based on different energy sources, and then adding them together.

- The emissions of system are obtained by calculating the emission from each process, and also the emission accompanying the conversion of energy use, and then sum them up.

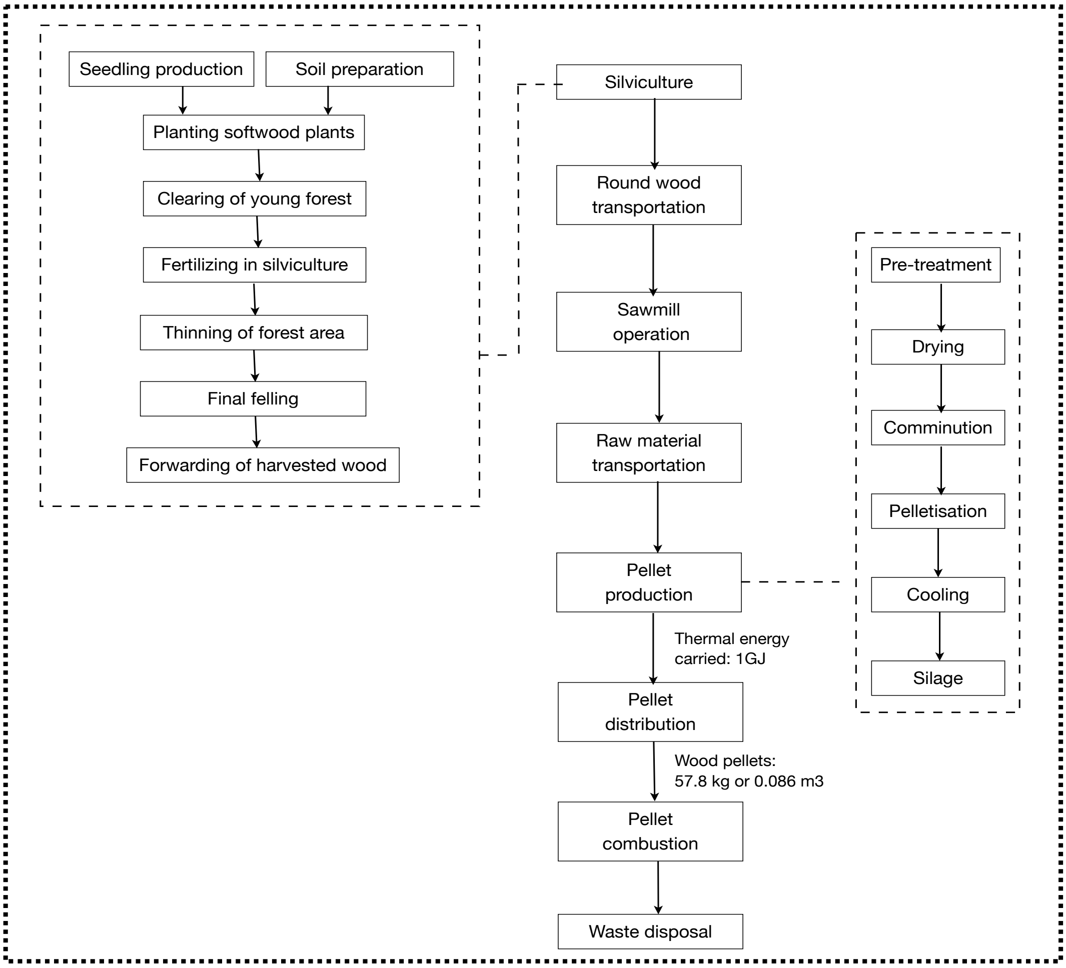

Figure 4.1 Flowchart for wood pellet industry

4.2.1 Energy

Electricity, biofuels and fossil fuels make up the three energy sources in the entire life cycle of wood pellet. In this study, energy is accounted in the unit Megajoule [MJ] for biofuels and fossil fuels usage, and electricity consumption is accounted for the unit Kilowatt-hour [kWh].

The environmental impact comes with energy use is well documented in some sources, whereas others are less easy to be assessed or quantified. Such environmental impact as emissions originated from combustion of fossil fuels during the transportation process is well established and accounted in the inventory study. However, environmental impacts regarding electricity consumption on the other hand, are in some degree not that easy to assess. It is common that in many places fuels are used to generate electricity, which gives birth to a risk of double counting if the part of electricity is by mistake counted together with electricity generated from primary energy, i.e. the part of energy flow passing the system boundary. According to Neova, there is no internal produced electricity that all the electricity is purchased.

In this study, when biofuels are used as energy source, the amount of certain fuel is sometimes noted twice, which for one time as illustrated in terms of the used energy (MJ), and for the other time as volume of the used fuel (m^3).

4.2.2 Material flow

When doing life cycle inventory analysis, the mass balance of each process needs to be first established with the functional unit as the basis of calculation, and then followed by the formulation of material flows. The generation of mass balance and material flows are discussed as following.

a - Raw material (sawdust) required in relation to f.u. (m^3)
b - Biofuel (barks) used in pellet plant in relation to f.u. (m^3)
c - Outcome products (wood pellets) in relation to f.u. (ton)
t - Timbers from forest. (m^3)
em - Emissions (g)

$$c = \frac{1 f.u.}{e_{woodpellet}} = 57.8kg \qquad (4.1)$$

where:
f.u. — Functional unit, 1000MJ
$e_{woodpellet}$ — Energy content of wood pellets, 17.3 MJ/kg

$$a = \frac{A}{C} \times c = 0.3757c \qquad (4.2)$$

where:
A — Annual consumption of raw material, which equals to 585000 m^3
C — Annual production of wood pellets, which equals to 90000 ton

$$b = \frac{B}{C} \times c = 0.0578c \qquad (4.3)$$

where:

B — Annual consumption of biofuel, which equals to 90000 m^3

$$t = \frac{T}{A'} \times a \tag{4.4}$$

where:

T — Total input round wood at the investigated sawmill

A' — Total output sawdust at the investigated sawmill

Since the emissions regarding energy use vary from one fuel to another, if such emissions are not measured or such data is not available at data providers, the estimate figures in table 4.1 have been used instead. These figures represent the emission factor for combustion different fuels in stationary incineration plants. The emissions in relation to transportation driven by fossil fuels are different which, however, followed the emission regulation of Euro engine class (see Appendix Ⅱ).

Table 4.1 Emission factors for fuel combustion in Stationary incineration plants, g/MJ supplied fuel (Tillman, Baumann et al. 1991)

Emission	Oil	Coal	Gas	Biofuel
SO_2	0.39	0.38	0.002	0.03
NO_x	0.15	0.15	0.15	0.15
CO	0.013	0.017	0.001	1
HC	0.018	0.01	0.000015	0.1
CO_2	80	92	55	-
PM	0.03	0.013	-	-
Ash	0.007	0.3	-	0.1
Oil (aq)	0.0004			
Phenol	0.0000057			
COD	0.0012			
Tot-N	0.00019			
Crude oil	26.13			
Electricity	0.000282			

$$em = \sum em_i = \sum em_{fossil-fuel} + \sum em_{biofuel} + \sum em_{other} \tag{4.5}$$

where:

em_i — Emissions from each life cycle process.

$em_{fossil-fuel}$ — Emissions from using fossil-based fuels, including transportation and stationary incineration plants.

$em_{biofuel}$ — Emissions from using biofuels

em_{other} — Other emissions.

Table 4.2 represents the mass-flows between each life cycle process in the flowchart (Figure 4.1). The calculation is based on the data from latter presented. To be noticed that the transportations are excluded as assuming no mass loss during the process, hence no mass changes. The mass-flows across the system boundary are not included in the table.

Table 4.2 Mass flows in the flow chart in relation to 1 f.u

From	To	Mass flow	Materials
Silviculture	Sawmill operation	Round wood	0.85 m^3
Sawmill operation	Pellet production	Saw dust Barks	0.38 m^3 0.06 m^3
Pellet production	Pellet combustion	Wood pellet	57.8 kg (0.086 m^3)
Pellet combustion	Waste disposal	Ash	1.8 kg

4.3 Inventory analysis

Inventory analysis is done by investigating the environmental performance of each life cycle process one by one. The inventory data is collected and calculated by first normalized for each process, then related to functional unit to calculation the energy and material flows linked to each life cycle process and passed the system boundary. Only aggregated environmental load parameters are given in the context, the entire inventory data can be found in appendix II.

4.3.1 Silviculture

Forestry supports the wood-related industry. For wood pellets industry, the raw material is basically originated from the timbers produced by forestry (although in some circumstance, many agricultural-based biomass, for example straw, would also be used in producing wood pellets in order to make up the shortage of sawdust, in this study, only sawdust is considered to be raw material of wood pellets). Therefore forest can be considered as the cradle of wood pellets production.

In Sweden, the general silviculture process includes eight steps, as it is stated below. The data is collect from the CPM LCA database, which is running by Chalmers, plus some literature data is used as reference (such as (Berg and Lindholm 2005) and (Aldentun 2002))

1. Plant nursing: to prepare seedlings. In this process, two machines with 6kW and 50% utilization is used for peat handling and sowing. 1000 plants are kept in 5 plastic cases, which can be used for 4 times. Tractors (60kW and 50% utilization) are used for transporting plants to greenhouse, where diesel oil is used to supply heat.
2. Soil preparation: to prepare the soil for growing trees. It is assumed that 22.5 liters diesel/ha is used to prepare 0.5 ha/h, which equal to 45 l diesel/ha resulting in 1602

Mj/ha (assuming 35.6 MJ/l diesel).

3. Planting: to plant tree seedlings. Trucks, with capacity of 40000 seedlings per truckload, are used to carry the seedlings from the seedling nursery to the forest. Tractors (30kW) are used in the forest. Fertilizer is assumed to be the same as it is used in the forest with 27.2% nitrogen content.
4. Clearing: to clear some plants in order to limit the competition and protect the best plants, by using a portable clearing saw.
5. Thinning: to conduct by using forest processor in order to raise the productivity of the remaining forest.
6. Fertilizing: to increase the growth rate of the plants. This is done one to three times by using tractors (14%) and helicopters (86%). Fertilizer in this study is considered as N-fertilizer with nitrogen content 27.2% (SKOG-CAN).
7. Final felling: to harvest the woods.
8. Forwarding: to transport the felled wood from felling area to the road side.

Table 4.3 illustrates the environmental load in relation to 1 functional unit of the Silviculture step.

Table 4.3 Environmental load of Silviculture associate with 1 f.u.

Parameter	Total	Unit
Use of resources		
Forest land	0.002	ha
Tree seeds	0.001	kg
Thinned forest area	0.002	ha
Copper ore	0.08	g
Iron ore	0.003	g
Lead ore	0.0009	g
Bauxite	0.000005	g
Uranium ore	0.05	g
Coal	0.0002	kWh
Oil	0.001	kWh
Natural gas	0.00005	kWh
Energy use		
Electricity *(internal parameter)*	0.1	kWh
Diesel	130	MJ
Gasoline	0.8	MJ
Kerosene	0.9	MJ
Biofuel		
Emission to air		
CO_2	10,569.2	g
CO	1.8	g
NO_x	20.0	g
HC	2.4	g
N_2O	0.7	g
SO_2	51.5	g
CH_4	0.9	g
Particles	4.0	g

Emission to water		
N-tot	0.0001	g
Waste		
Highly active radioactive waste	0.002	g
Low active radioactive waste	1.04	μg
Building waste	0.003	g

4.3.2 Sawmill operation

Sawmill is the place where the trees are debarked and transformed into many other wood related products, for example: boards, timbers and so on. In the mean time, accompany with the main products, a large quantity of wood byproducts has been yield during the process, which includes for example sawdust, barks, wood chips and so on. These byproducts are able to take approximately the same size of volumes as the main products, and used to be treated as waste to be dumped or burned directly. However, due to the energy and economic concerns, the byproducts of sawmills are no longer waste, instead they are widely used in downstream wood-related industries to produce, for example, wood pellets and other biofuels.

The environmentally related data regarding sawmill operation over the entire country is generally not available. Instead, in this study, data for proceeding allocation is by collecting and analyzing the environmental declaration of several sawmills, mainly according to (STORAENSO 2004). Plus several scientific reports are also used as reference to examine the result of allocation.

Even though the economic-oriented allocation method is adopted in this study to treat encountered allocation problems, and only the results from the economic-oriented allocation method are presented and go to the final conclusion, I would like to make the comparison of the three allocation methods proposed in section 3.5 by using the collected inventory data at the sawmills.

Depending on which allocation method is used, the results usually vary from one approach to another. For the method using volume-based allocation factor, it has the advantage that can avoid considering the moisture content of the wood, and therefore to avoid the uncertainty originated from different types of wood. But using volume as basis for partitioning environmental load has a disadvantage that the measurement of volume is somehow arbitrary, which may give birth to uncertainty as well. To attribute all environmental loads to the main product, and treat other byproducts as wastes, which is free of causing environmental load, is another way to deal with allocation. But this method is relatively too crude to show the effects of byproducts to the environment, especially when the quantity of byproducts is large and the byproducts share certain functions with the main product. The third allocation approach is based on the relative economic value of each byproduct. It is not uncommon that the fluctuation of market price of the products may have influence to the result of the allocation. However, in this project, according to the statistics made by Swedish Energy Agency, although the market prices of wood-related products, especially the wood-based fuels, are slowly increasing over the passed few years, they can be seen as fairly stable, due to no big fluctuation has been identified. Furthermore, another reason for economic-oriented allocation outweighs the rest allocation methods is that, for the sawmill, it is profit that makes it run, and thus more reasonable to have the environmental loads allocated in relation to the profit made by its different products.

According to the allocation methods, the environmental load of sawmill operation must be divided and distributed to each of the sawmill products. Therefore the allocation factors, which based on relative volume relationship and economic value of each product are given by equation 4.6, 4.7. The relative economic value of each product is based on the average market price, which given in table 4.4.

$$f_{volume} = \frac{V_i}{\sum V_i} \qquad (4.6)$$

where:

f_{volume} — Allocation factor based on relative volume

V_i — Volume of certain byproduct from sawmill

$\sum V_i$ — The total volume of all products from sawmill

$$f_{price} = \frac{V_i \cdot P_i}{\sum V_i P_i} \qquad (4.7)$$

where:

f_{price} — Allocation factor based on relative economic value (market price)

P_i — Market price of 1 m^3 certain byproduct from sawmill

Table 4.4. Reference market price of byproducts from sawmill (Lundmark 2006)

	Timber	Pulp wood	Sawdust	Bark	Wood chip
Market price (SEK/CUM)	390	230	120	130	90

Table 4.5 given the calculated allocation factors that using in this report.

Table 4.5 Allocation factors based on volume and market price

	Allocation factor (volume)	Allocation factor (price)
Sawn logs	0.2199	0.3888
Pulpwood	0.3842	0.4007
Sawdust	0.2042	0.1111
Barks	0.1173	0.0691
Wood chips	0.0744	0.0304

According to the allocation factors, the environmental loads are partitioned and distributed to each of the sawmill products in relation to functional unit. Table 4.6 only shows part of the allocation results, the entire results can be found in appendix II.

Table 4.6. Comparison of the environmental load of the three different allocation approaches for sawmill operation

Aggregated over system	Flows passing system boundary; UNAILOCATED	Allocated based on relative volume	Allocated all to sawn timber	Allocated based on market price
Electricity use at the sawmill				
Sawn timber	25.6224	5.6342	25.62	9.9617
Pulp chips		9.8452	0.00	10.266
Sawdust		5.2315	0.00	2.8461
Bark		3.0046	0.00	1.7708
Chip		1.9070	0.00	0.7781
CO2 emissions at the sawmill				
Sawn timber	1753.6469	385.6141	1753.6469	681.7988
Pulp chips		673.8257	0.0000	702.6097
Sawdust		358.0512	0.0000	194.7893
Bark		205.6378	0.0000	121.1951
Chip		130.5181	0.0000	53.2540

Even though the environmental loads are allocated to different products, only sawdust and barks used as raw materials and fuels for wood pellets production enter the next process. Therefore only the environmental load initiated from sawdust and barks are account into the study.

Table 4.7. Environmental load of Sawmill Operation associate with f.u.

Parameter	Total	Unit
Use of resources		
Timber	0.9	m^3
Copper ore	3.4	g
Iron ore	0.1	g
Lead ore	0.04	g
Bauxite	0.0002	g
Uranium ore	2	g
Coal	0.007	kWh
Oil	0.06	kWh
Natural gas	0.002	kWh
Energy use		
Electricity*(internal parameter)*	3.3	kWh
Thermal energy	82.0	MJ
Biofuel	39.0	MJ

Solid energy	2.7	MJ
Emission to air		
CO_2	318.7	g
CO	41.7	g
NO_x	5.5	g
HC	3.9	g
SO_2	1.2	g
Particles	0.02	
Emission to water		
N-tot	0.004	g
Waste		
Ash	0.0001	m^3
Hazardous waste	1.1	g
Other waste	10.2	g
Highly active radioactive waste	0.07	g
Low active radioactive waste	44	μg
Building waste	0.1	g

4.3.3 Pellet production

The detailed processes of wood pellets production have been stated earlier, which can be refer to figure 2.1. The site-specific data was collected at the pellet plant by personal interviews. Additionally several statistic reports as well as measurement reports provided by Neova also served as the data sources.

The pellet plant is located southwest of Vaggeryd's urban area. Estimated running time of the plant is approximately 7000 hours per year (Johansson 2006), with a capacity of producing 90000 tons of wood pellets, by consuming 585000 m^3 sawdust (Ebb 2009). The raw materials are fed into a so-called INCUBATOR-filter, where the sawdust is preheated by letting flue gas pass through. Then preheated materials are transported to a rotary drum dryer, which is connected to the solid wood boiler. The fuel of the boiler consists of byproducts from the forest industry, mainly barks and wood chips. With the waste gases, the material in the drum is dried from about 53% moisture down to approximately 15-18%. Then the dried material is separated from flue gas via a cyclone for further transport to an interim storage. Flue gases are then diverted through a 17.6m high stack. The interlayer material is transported to a hammer mill where the raw materials are down to fraction less than 3 to 4 mm. A certain amount of steam is added to the fined sawdust to increase its adhesion and resistance to crumble. Thereafter, the raw material is pressed into small cylindrical rods (pellets) with a diameter of 6 - 12 cm. Pellets are cooled and sieved after pressing. Air evacuated from the pellet cooler is purified through cyclone separators. The concluding operations are intermediate packaging and loading the truck for further transport to the customer. Pellets are delivered either in bulk or in bag. Internal transportation involves small fork trucks, which is using diesels. It is estimated that half of the internal transporters are following the European Standard 2, the rest are following Standard 3.

Table 4.8. Environmental load associated with Pellet Production process associate with f.u.

Parameter	Total	Unit
Use of resources		
Sawdust	0.4	m^3
Copper ore	9.7	g
Iron ore	0.3	g
Lead ore	0.1	g
Bauxite	0.001	g
Uranium ore	5.6	g
Coal	0.02	kWh
Heavy oil	0.2	kWh
Natural gas	0.01	kWh
Energy use		
Electricity *(internal parameter)*	9.4	kWh
Biofuel	137.0	MJ
Diesel	1.8	MJ
Emission to air		
CO_2	392.5	g
CO	32.6	g
NO_x	18.3	g
HC	14.0	g
SO_2	0.5	g
Particles	0.09	g
Terpenes	24.0	g
Emission to water		
N-tot	0.01	g
Waste		
Ash	11.0	g
Highly active radioactive waste	0.2	g
Low active radioactive waste	124.7	µg
Building waste	0.3	g

4.3.4 Transportation

The means for transportation are varying, depending on the distance and amount of cargo needed to be transported. There are at least three transportation processes are identified in the entire life cycle of wood pellet production.

- Transport round wood from felling ground to sawmill
- Transport sawdust and barks from sawmills to the pellet plants
- Transport wood pellets from the pellet plants to customers

It is estimated that the average distance for transporting newly felled round wood to sawmills is about 80 km (Jönsson 1995). Round wood is carried by heavy lorries, and the wood is assumed to have the same bulk density as it is at the felling ground. In this study, the product is mainly made from softwood material, and according to Jönsson 1995, the bulk density of newly felled pine is around 775 kg/m3 with 70% moisture content.

Data for raw material transportation and products distribution are collected from the logistic department of Neova. Approximately the distance for forwarding wood pellet to large-, middle- and small scale customers is about 170, 180 and 165 kilometers respectively, and it is 100 kilometers for transporting raw materials and fuels from sawmills to the pellet plant. Heavy trucks with one bar trailer and 38 tons payload are considered to be the only transportation tools. To be simplified, it is assumed that all the sawdust during the transportation process shares the same bulk density of 240 kg/m^3 at 50% moisture content, and so does the barks of 320 kg/m^3 (Loo and Koppejan 2008).

Table 4.9. General info. of transportation process

<table>
<tr><th rowspan="2">Transportation Activity</th><th rowspan="2" colspan="2">Distance</th><th colspan="4">Engine type</th></tr>
<tr><th>Euro 2</th><th>Euro 3</th><th>Euro 4</th><th>Euro 5</th></tr>
<tr><td>Round wood transportation</td><td colspan="2">80 km</td><td>0</td><td>50%</td><td>50%</td><td>0</td></tr>
<tr><td>Raw material Transportation</td><td colspan="2">100 km</td><td>0</td><td>50%</td><td>50%</td><td>0</td></tr>
<tr><td rowspan="3">Wood pellet Distribution</td><td>To Small-scale customers</td><td>165 km</td><td>10%</td><td>40%</td><td>33%</td><td>17%</td></tr>
<tr><td>To mid-scale customers</td><td>180 km</td><td>0%</td><td>50%</td><td>50%</td><td>0%</td></tr>
<tr><td>To large-scale customers</td><td>170 km</td><td>2%</td><td>60%</td><td>36%</td><td>2%</td></tr>
</table>

Table 4.10. Environmental load associated with transportation associate with f.u.

Parameter	Amount	Unit
Energy use		
Diesel	31.8	MJ
Emission to air		
CO_2	2374	g
CO	3.3	g
NO_x	15.9	g
PM	0.3	g
HC	1.04	g
CH_4	0.03	g
SO_2	0.01	g
N_2O	0.02	g

4.3.5 Use Phase

The most common use of wood pellets is to burn to get heat or generate electricity. Therefore either in large-scale combustion heat plant or in household use, a boiler for burning is necessary. The customers of Neova are classified by the size of the boilers they used, as small-, mid- and large-scaled customer, which are specified as:

- Large-scale, include for example heat plants/CHP plants, with thermal output larger than 2MW) (Höglund 2008);
- Middle-scale, include for example Heat centrals, schools and industries with thermal output between 50 kW to 2 MW (Höglund 2008);
- Small-scale include for example Detached houses and smaller properties, with thermal output less than 50kW (Höglund 2008).

Data regarding burning wood pellets at large-scale combustion heat plant and mid-scale customers' are collected directly from CPM LCA database. The data is based on a gate-to-gate LCA of incineration process in wood pellets fired plant for heat and power production, which are located in Sweden. The produced heat from the plant is delivered to a district heating system. In order to simplify the study, when both heat and electricity are produced at the same time, the allocation between heat and electricity is treated as equal, which means the environmental load caused by producing 1 kWh of heat is equal to 1 kWh produced electrical power.

The emission and resource use factors vary largely from case to case for small-scale users. Perhaps this is because the wood pellet appliances and burners installed in single-family house are quite different from one to another. A well-designed pellet-fired system is able to achieve a fairly high efficiency, usually over 80%, whereas on the other hand, the efficiency of many pellet stoves may reduce to 50-60% due to a high excess air level (Loo and Koppejan 2008). For Swedish context, the capacity of a typical pellet boiler to produce heat in households is $11kW_{heat}$ with the net efficiency 78% (Gustavsson and Karlsson 2001). An LCA software "Global Emission Model for Integrated System, Version 4.5 (GEMIS4.5)" was used to simulate the combustion of wood pellets in household users. The parameters for simulating are set to fit the typical Swedish household pellet boiler.

Table 4.11. Environmental load associated with wood pellets combustion associate with f.u.

Parameter	Amount	Unit
Use of resource		
Copper ore	10.6	g
Iron ore	0.3	g
Lead ore	0.1	g
Bauxite	0.001	g
Uranium ore	6.2	g
Coal	0.02	kWh
Heavy oil	0.2	kWh
Natural gas	0.01	kWh
Energy use		
Electricity *(internal parameter)*	10.2	kWh
Emission to air		
CO_2	281.8	
CO	81.8	g
NO_x	69.2	g
HC	0.04	g
SO_2	15.5	g
PM	15	g
CH_4	2.5	g
N_2O	0.5	g
Emission to water		
N-tot	0.01	g
Waste		
Ash	1801.0	g
Waste oil	1.8	g
Other waste	16.3	g
Highly active radioactive waste	0.2	g
Low active radioactive waste	136	μg
Building waste	0.3	g

4.3.6 Waste management

In reality, the ash of burned wood pellets is treated variously. In some cases, the ash is used as a layer in covering up waste materials, whereas in other circumstance ash is spread in the forest as fertilizer or deposited in landfills. Nevertheless, sustainable biomass utilization requires to close the material fluxes and to integrate the biomass ashes within the natural cycles, which indicates that the cycle of minerals should be closed as completely as possible. So it is recommended to have ash from wood or bark combustion recycled in forestry areas.

Soil/nutrients → root/plant → combustion → ash → soil (Loo and Koppejan 2008)

However, wasted ash sometimes contains certain quantity of heavy metals, especially ash from combustion plant. To deposit the heavy metal-contained ash on the forest will also disturb the natural cycle of minerals and result in environmental pollution. Therefore it is recommended to have some additional treatment to separate unpleasant contents of the ash before deposition. But this has already beyond the scope of this study and thus not necessary to dig deeper.

For Neova, the treatment of biofuel waste is usually crude, either by spreading the ash in the nearby forest, or by using it as a kind of filling material to cover up other disposed wastes. The environmental impacts caused by those operations are treated to be neglect. For large combustion facilities, the emission from the transportation of ash to the deposit will have negative effect to the environment, but the data at this part is not available. Besides the environmental impacts result from transporting ash may be much smaller compared with transporting raw material and products, since the quantity of ash in relation to the function unit is much smaller, and the mean distance for delivering the incinerated waste to nearby landfills is about 15 km (Baumann and Tillman 2004), which is also very small compared with the hundreds of kilometers for raw materials and production transportation.

4.4 Inventory Result

In most cases, it is common to have a large number of inventory parameters when life cycle inventory analysis is complete, which makes the results less understandable. However, since this project is relatively small, only several important parameters are selected to investigate. The inventory result parameters to produce one functional unit of wood pellets are presented in table 4.12. The detailed inventory results can be found in Appendix Ⅱ.

To facilitate interpretation of the inventory results, it is necessary to group the parameters into categories and illustrate in a relatively simple way to be apprehended. The inventory parameters in this report are grouped into three categories as use of resources, energy use, and emissions to the air and water. The results are demonstrated in forms of bar diagram, in order to compare the environmental performance of the each activity of the entire life cycle process.

Table 4.12 Environmental load over the entire life cycle of wood pellet

Parameter	Total	Unit
Use of resources		
Timber	0.9	g
Copper ore	23.8	g
Iron ore	0.8	g
Lead ore	0.3	g
Bauxite	0.002	g
Uranium ore	13.8	g
Coal	0.005	kWh
Oil	0.4	kWh
Natural gas	0.001	kWh
Energy use		
Fossil fuel	251	MJ
Electricity *(internal parameter)*	22.5	kWh
Biofuel	176	MJ
Emission to air		
CO_2	13,936	g
CO	162	g
NO_x	129	g
HC	21	g
N_2O	1.3	g
SO_2	69	g
CH_4	3.4	g
Particles	19	g
Emission to water		
N-tot	0.03	g
Waste		
Ash	1811	g
Waste oil	1.8	g
Building waste	0.8	g
Highly active radioactive waste	0.5	g
Low active radioactive waste	0.3	g
Hazardous waste	1.1	g
Other waste	16.3	g

4.4.1 Use of Resources

The demand of resources for manufacturing wood pellets is not big since the raw material is only sawdust, a by-product from sawmill operation. The demand of wood resource is therefore allocated to different by-products at sawmill. The demand of other natural resources is barely originated from the production of electricity. In the entire course of life cycle, it is the sawmill operation, pellet production and pellet combustion that require electricity, so that the resource demand of these processes is relatively big.

The results are illustrated in figure 4.2. Beware the unit for each parameter is not exactly the same.

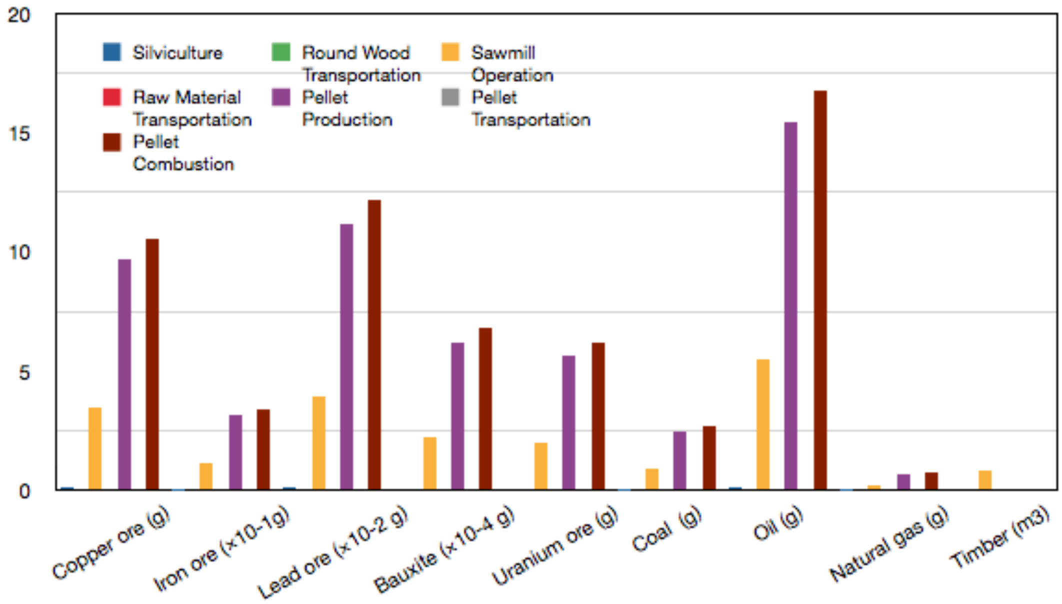

Figure 4.2 Use of resources during each life cycle process

- Figure 4.2 indicates a clear relationship between the depletion of natural resources and the consumption of electricity, if compared with Figure 4.4. For each of the life cycle process, the more electricity it consumes, the more natural resources it depletes.

4.4.2 Emissions

Data of emissions to the air and water are aggregated and documented in Table 4.12, the results are shown in Figure 4.3. Beware that the unit for each parameter is different from one to another.

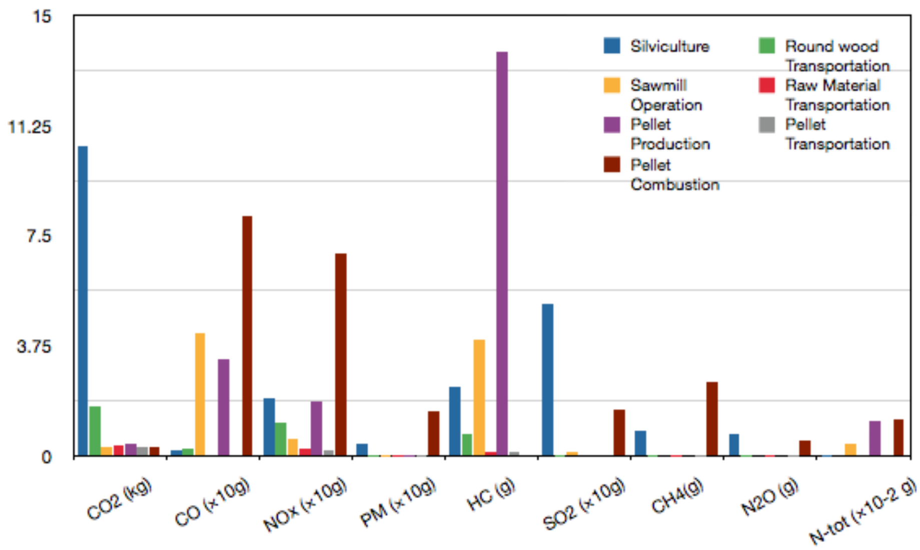

Figure 4.3 Emissions to air and water of each life cycle process

The inventory results of emissions are demonstrated in Figure 4.3, which indicates:

- Pellet Combustion is one of the least environmental preferable processes in the entire course of life cycle, which has the largest contribution to the emissions of CO, NO_x, PM, CH_4 and N-tot. Since the combustion of wood pellets is CO_2 free, the part of CO_2 appears in this step comes from the electricity production.
- Silviculture step has very big contribution of emissions to the air as well. Especially the emission of CO_2 is way bigger than the rest life cycle processes, which to a large extent is due to the considerable consumption of fossil fuel. The use of fossil fuel also gives birth to a high emission of SO_2.
- By comparing Figure 4.4, it is not difficult to find the relationship between the use of fossil fuel and the emission of CO_2. Since biofuel is treat as CO_2 emission free, CO_2 emission, during the entire life cycle of wood pellets is due to the use of fossil fuel. Therefore to reduce the fossil fuels usage will improve the environmental performance of wood pellets.
- Pellet Production process has a remarkably higher HC emission than the rest of the life cycle. The most possible explanation could be due to the incomplete burning of a mass of barks.
- N-tot is the only emission to water, which is associated with the production of electricity.

4.4.3 Energy use

Fossil fuels, biofuels and electric power consist the three energy sources to provide energy in producing wood pellet. The energy use of each life cycle process in relation to functional unit is shown in Figure 4.4.

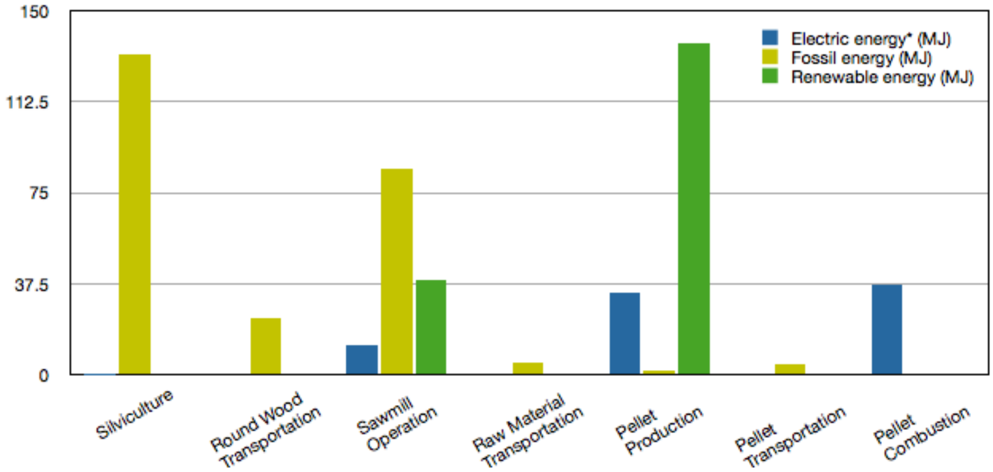

Figure 4.4. Total use of energy in each life cycle process

The inventory results of energy use are demonstrated in Figure 4.4, which indicates:

* The electricity is noted as an internal parameter.

- Silviculture is the most fossil energy dependent process that consumes a lot more fossil energy than other life cycle processes. This is due to the use of large fossil fuel-driven machines during silviculture.
- The Pellet Production process is the most energy-consuming process according to Figure 4.4. This is because the drying, grinding and pelleting steps within the pellet plant are all requires a large quantity of energy. In total the Pellet Production requires about 172 MJ energy to produce 57.8 kg (1 functional unit) wood pellets, which roughly equals to 17% of the energy contained in the wood pellets delivering to the customers.
- The electricity consumption of Pellet Combustion process comes from the ignition and automatically feeding of wood pellets to pellet burners.

5. Life Cycle Impact Assessment

If the life cycle inventory data attribute some emissions to certain environmental themes or impact categories, it does not imply that real damages or effects has been made by the studied product or system, instead it emphases the potential to initiate such impact. Therefore life cycle impact assessment is about to assist to determine to what extent that a particular product or process's emissions may be associated with particular impact category. It will broaden the information and context of life cycle inventory data. More specifically it will translate the LCI data into environmental impact and thus to describe the potential environmental consequences.

5.1 Impact definition

As it is decided in Goal and Scope Definition chapter, the main environmental impact categories are classified as:

- Resources depletion;
- Human health;
- Ecological consequences

According to the results of inventory analysis, these three main categories can be further divided into sub-categories as:

- Resource depletion
  Energy depletion
  Material depletion

- Human health
  Toxicological impacts

- Ecological consequences:
  Global warming
  Acidification
  Eutrophication
  Photo-oxidant formation

5.2 Impact classification

Impact classification is about to have the parameter results from inventory analysis sorted and assigned to the different impact categories stated in last section.

Ecological consequences:
-Global warming: CO_2; CH_4; N_2O
-Acidification: SO_2, NO_x
-Eutrophication: NO_x
-Photo-oxidant formation: CO, NO_2, SO_2, CH_4

Toxicological impacts: SO_2, PM_{10}, NO_2

Resources depletion: Oil, Natural gas, Hard coal, Fossil energy, Iron, Copper, Lead, Bauxite, Uranium

5.3 Impact characterisation

Impact characterisation is a quantitative step to translate the environmental load into impact. This translation can be realized by introducing equivalency factors, which are determined by the contribution of different substances to the different impact categories according to the physico-chemical mechanisms of the substances, i.e. according to the natural sciences (Baumann and Tillman 2004). For example, the size of acidification is calculated by summing up all the acidifying emissions (SO_2, HCl etc.) based on the equivalency factor of each pollutant, where the equivalency factor is defined by the nature and ability of the pollutant to release H^+.

In this paper, the methods to determine the equivalency factors are not included, since the description of the methods usually calls for a good understanding of natural science. To explain the knowledge of such natural science is beyond the scope of this study. Additionally some of the characterisation methods are less developed due to the mechanisms of the impact are more complicated and still not fully understood by humans (e.g. eco-toxicity) (Baumann and Tillman 2004).

Impact characterization in this study is based on the characterization indicators demonstrated in Table 5.1. The table does no include all the indicators for each environmental impact. Interested readers can refer to the original sources for complete indicators.

Table 5.1. Characterization indicators

Global warming (IPCC 2003)

Trace Gas	GWP[1] 20 years (kg CO_2 eqv / kg)	GWP 100 years (kg CO_2 eqv / kg)	GWP 500 years (kg CO_2 eqv / kg)
CO_2	1	1	1
CH_4	62	23	7
N_2O	275	296	156

1. *Global warming potentials (GWP) for different time horizons expressed in kg of the reference substance CO_2*

Climate change = $\sum_i GWP_{a,i} \times m_i$ *(Guinée 2002)*

where, $GWP_{a,i}$ is the Global Warming Potential for substance i integrate over years;
m_i(kg) is the quantity of substance i emitted

Remark: Although SO_2 is known to have negative influence on enhancing the climate forcing effect, the GWP value for SO_2 is not known yet.

Human toxicity: (Huijbregts 2000; Guinée 2002)

Substance	HTP[2] (20 yr)	HTP[2] (100 yr)	HTP[2] (500 yr)	HTP[2] (inf)
PM_{10}	0.82	0.82	0.82	0.82
SO_2	0.096	0.096	0.096	0.096
NO_2	1.2	1.2	1.2	1.2

2. *Human toxicity potentials (HTPinf) are expressed in kg of 1,4dichlorobenzene equivalent.*

HTP factors for characterizing human toxic releases, for infinite, 20, 100 and 500 year time horizons and global scale

human toxicity = $\sum_i \sum_{ecom} HTP_{ecom.i} \times m_{ecom.i}$ *(Guinée 2002)*

where: $HTP_{ecom.i}$ is the Human Toxicity Potential (the characterisation factor) for Substance emitted to emission compartment ecom (air, water etc.)
m_i is the emission of substance i to medium ecom.

Photochemical ozone creation potential (Derwent, Jenkin et al. 1998; Guinée 2002)

Substance	High NO_x POCPs[3] (kg ethylene / kg	Low NO_x POCPs (kg ethylene / kg	MOIRs (kg formed ozone/ kg
CO	0.027	0.04	0.029
NO_2	0.028	-	-
SO_2	0.048	-	-
CH_4	0.006	0.007	0.007

3. The result of the indicator is expressed in kg of the reference substance, ethylene. Photochemical ozone creation potentials (POCPs) for high NO_x and low NO_x background concentrations expressed relative to ethylene.

oxidant formation = $\sum_i POCP_i \times m_i$ *(Guinée 2002)*

where: $POCP_i$ is the Photochemical Ozone Creation Potential for substance i
m_i(kg) is the quantity of substance i emitted

Acidification (Guinée 2002)

Substance	AP (g $SO_{2\ eqv}$ / g)[4]
SO_2	1.2
NO_x	0.5

4. Generic acidification equivalents expressed in kg of SO equivalents.

$$\text{acidification} = \sum_i AP_i \times m_i \quad \text{(Guinée 2002)}$$

where: AP_i is the Acidification Potential of substance i emitted to the air
m_i is the emission of substance i to the air

Remark: This is the average European AP factor for characterizing acidifying releases to the air

Eutrophication (Heijungs, Guinée et al. 1992; Guinée 2002)

Substance	$(g\ PS_4^{3-}{}_{eav}/g)^5$
NOx	0.13
NO_2	0.13

5. Generic eutrophication equivalents for emission to air is expressed in kg of PO equivalents.

$$\text{eutrophication} = \sum_i EP_i \times m_i \quad \text{(Guinée 2002)}$$

where: EP_i is the Eutrophication Potential for substance i emitted to air
m_i is the emission of substance i to the air

Depletion of abiotic resources (Guinée 2002)

Substance	ADP (in kg antimony eq./kg)	
Iron	8.43E-08	
Copper	1.94E-03	
Lead	1.35E-02	
Bauxite	1E-08	
Uranium	2.87E-03	
Oil	2.01E-02	
Natural gas	1.87E-02	(in kg antimony/m^3 natural gas)
Hard coal	1.34E-02	
Fossil energy	4.81E-04	(in kg antimony/MJ fossil energy)

6. Abiotic Depletion Potential of resource is expressed in kg of the reference resource antimony. For fossil energy, abiotic depletion potential is expressed in kg antimony eq./MJ fossil energy

$$\text{ADPfossil energy} = \frac{DR_{fossilenergy}}{(R_{fossilenergy})^2} \times \frac{(R_{antimony})^2}{DR_{antimony}} \quad \text{(Guinée 2002)}$$

Where: Rfossil energy is the ultimate reserve of fossil fuels in MJ;
DRfossil energy is the de-accumulation, or fossil energy production in MJ/yr
Rantimony is the ultimate reserve of antimony, the reference resource in kg
DRantimony is the de-accumulation of antimony, the reference resource in kg/yr

By following the characterization factors, the environmental load of each life cycle process has been translated into specific environmental impacts, whose results are illustrated in figure 5.1. The results from the level of impact characterization indicate:

- It is obvious that the Silviculture and final Pellet Combustion are the two processes contribute to the major environmental impacts in the entire life cycles.
- For Silviculture, its considerably big global warming potential (GWP) and other relative environmental impacts can be explained as the massive use of fossil fuel-driven machines during the tree-growing period, from seedling to harvest.

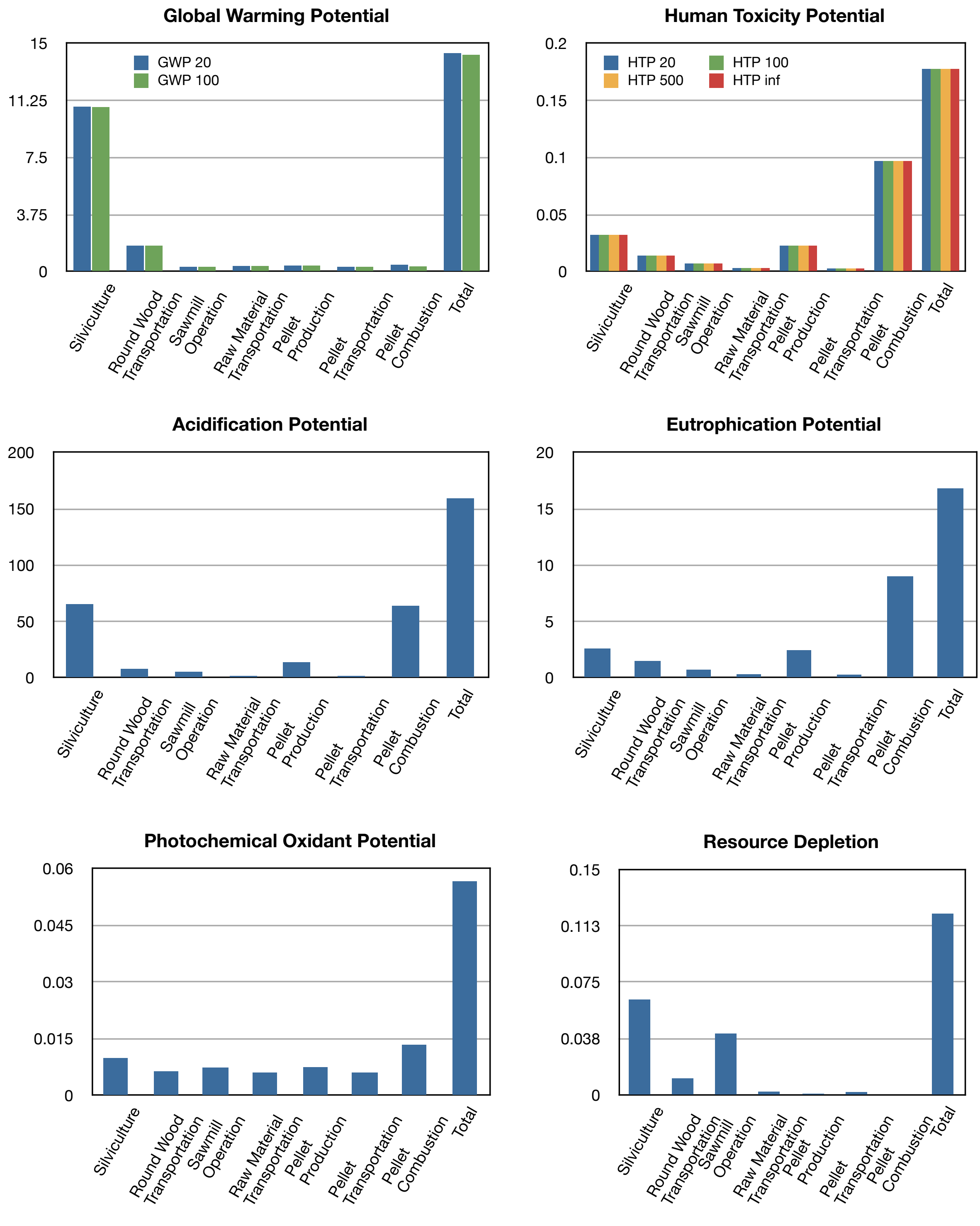

Figure 5.1 Results of Characterization

- For Pellet Combustion, even though the GWP is tiny, other environmental impacts are relatively high owing to a large quantity of air emissions associated to combustion.
- Except the Silviculture and Pellet Combustion, compared with the rest life cycles, the activities in Pellet Production process have relatively big influence on acidification, eutrophication and ground level ozone formation, which is related to the emission of nitrogen oxide, hydrocarbons, and sulfur dioxide result from burning, especially incomplete burning of barks and wood chips.
- Similar with Pellet Production, the Sawmill Operation is, however, with high potential on resource depletion. This is because the demand of timber, which is consider as a natural resource is accounted in this step, plus the use of fossil fuel, makes it the second place of resource depletion in the life cycle, barely behind the Silviculture.
- The environmental impacts in relation to transportation process is, however, not very significant.

5.4 Weighting

The environmental impacts needed to be weighed against one to another to see which environmental impact is relatively important. Therefore the process of weighting is a qualitative or quantitative process to measure the severity of different environmental changes. But unlike the characterisation process, which based on natural science, the weighting factors used to weight the environmental impacts also involves aspects of social science, such as monetarisation, authorized targets, technology abatement etc. (Baumann and Tillman 2004). The reason to introduce weighting process in LCA is that it will help to enhance the relevance and acceptability of LCA results. However, it is worthy to point out that the weighting step is less than a true measure of the aggregated impact, but more like a test of the compatibility of environmental impacts and other different values results from LCA study (Baumann and Tillman 2004).

In this paper it is not necessary to elaborate how exactly to define the weighting factors, instead, some ready-made LCIA methods are adopted, which avoid going in-depth of the procedures of each environmental impact assessment step (classification, characterization, etc.), but has the environmental information aggregated and go all the way down to weighting step.

There are several LCA weighting methods have been developed up to present, such as EDIP'97 - Environmental Design of Industrial Products; Ecoindicator'99; EPS 2000 - Environmental Priority Strategic in product development; Ecological scarcity 1997; Environmental themes and so on and so forth . A general review of all these methods turns out a fact that the results of using different weighting methods sometimes shown considerable difference (Bengtsson and Steen 2000), which means no such best option exits that can be standardized of choosing the weighting method. Different methods deliver different information to decision-making process from different perspectives, for example the Danish policy targets represent the value source of EDIP method, whereas the concept of society's willingness to pay to avoid damages dominates the EPS2000 method.

In this thesis, three weighting methods are used: *Ecoindicator'99*, *EPS2000 and EDIP*. The reason for such selection is owing to the difference between the modeling principles of each method, and also the different ways of interpreting the values or preferences. The main characteristics of these two methods are summarized in table 5.2.

Table 5.2. Main characteristics of the applied weighting methods in the thesis (Bengtsson and Steen 2000)

	Ecoindicator'99	**EPS2000**	**EDIP**
Effect modeling	Damages	Damages	Impact categories
Value source	Panel representing different perspectives	Society's willingness to pay to avoid damages	Danish policy targets
Geographical scope	Europe	World	Denmark
Parameters handled			
Emission	Yes	Yes	Yes
Resources	Yes	Yes	Yes
Work environment	No	No	Yes

5.4.1 Damage modeling

The first two methods are damage modeling methods, where environmental impacts are modeled to the damage level.

Ecoindicator'99

For the Ecoindicator'99 method, the damages to ecosystems, human health and finite resources are modeled according to the relevant environmental impacts, and generally covered the average European conditions. Additionally, this method is particular to use cultural values that determine the weighting factors. Specifically the individualist, the hierarchist and the egalitarian perspectives are the three cultural perspectives represented in Ecoindicator'99 (Baumann and Tillman 2004). The individualist and egalitarian perspective represent the two extreme situation of treating environmental impacts. For the individualist set of induce, it counts environmental impact barely on those proved cause-effect relations and sometimes short-term impact. But to the egalitarian view of point, it gives the precautionary principle to all possible environmental impacts, and thus most complete but somehow most uncertain at the same time. The hierarchist view is in between that the facts it provided needed to be backed up by scientific and political bodies (Baumann and Tillman 2004).

The weighting indices of Ecoindicator'99 used in this report is according to (Goedkoop and Spriensma 2001), and the weighting results of using Ecoindicator'99 for assessing the environmental impact of each life cycle is illustrated in figure 5.2.

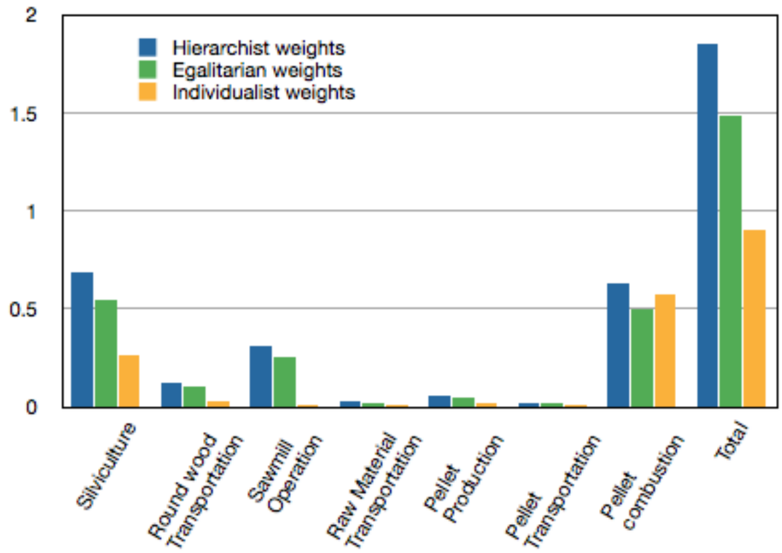

Figure 5.2. Environmental impact assessed with the Ecoindicator'99-method over the entire life cycle

The Ecoindicator'99-method indicates:

- The importance of environmental impacts in relation to the steps of Pellet Combustion and Silviculture is clearly more significant than the rest of life cycles, followed by Sawmill Operation, Round Wood Transportation.
- The importance of environmental impacts caused by Pellet Production, according to Ecoindicator'99-method, is not very magnificent.

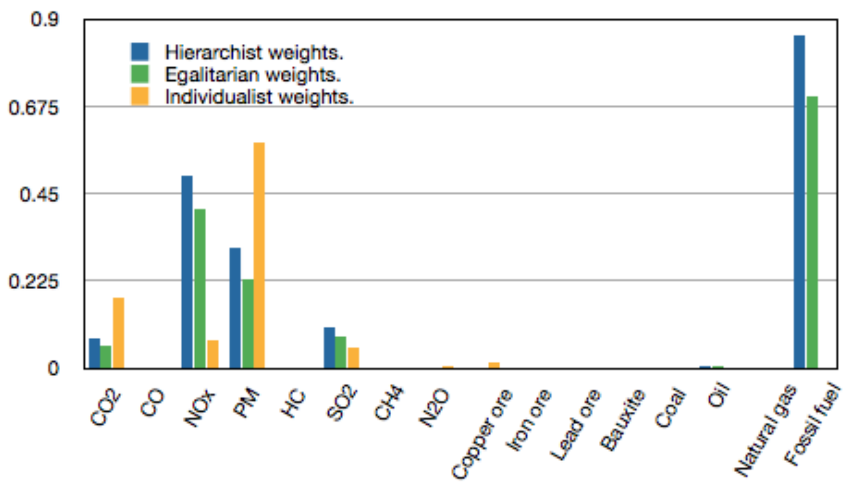

Figure 5.3. Main indices for environmental impact assessment with Ecoindicator'99-method over the entire life cycle

- The depletion of fossil fuel, according to the Ecoindicator'99-method, is the most significant parameter, followed by the emissions of nitrogen oxides, particle matters, sulfur dioxide and carbon dioxide.
- It is obvious that the Ecoindicator'99-method weights the environmental impacts associated with the emissions of NO_x and PM heavier than other emissions. This could probably explain why the final combustion of wood pellet cause relatively big environmental impact since much NO_x and PM is released during the burning process.
- The method weights the depletion of natural resource fairly light that the environmental impacts in relation to the depletion of mineral resources and fossil resource are both weighted light.

EPS2000

In the EPS2000 method, the damage modeling is based on the society's willingness to pay to avoid the changes on the five safeguard subjects - human health, biodiversity, finite resources, production capacity of harvested ecosystems, recreational and cultural values and the damage is based on world averages (Steen 1999). When it comes to assess the environmental impacts, due the large uncertainties involved, it is not easy to clear the gap between the potential and the real environmental impacts. But EPS2000 has an advantage that it tries to reflect real environmental impacts by adding an uncertainty factor to each index (Baumann and Tillman 2004).

The weighting indices of EPS2000 used in this report is according to (Steen 1999; Steen 1999), and the weighting results of using EPS 2000 for assessing the environmental impact of each life cycle is illustrated in figure 5.4

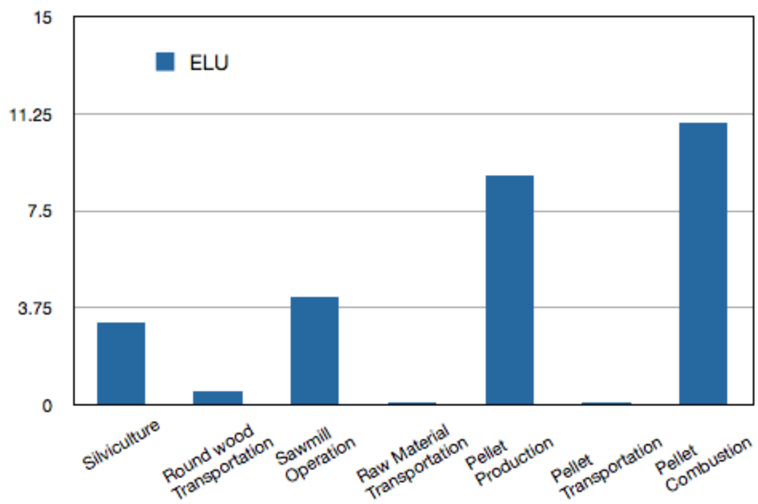

Figure 5.4. Environmental impact assessment with the EPS 2000-method

The results come with using the EPS 2000-method shows a different picture.

- In the EPS 2000-method, the environmental impact associated with Silviculture shows less significance to Sawmill Operation, Pellet Production and Pellet Combustion.
- Pellet Combustion still the least environmental preferable process. However, the Pellet Production is weighted much heavier than it is in Ecoindicator'99-method, that makes it become the second rank in environmental impact significance.
- One thing need to be noticed is that process with relatively more electricity demand, earns more weights in EPS2000-method, which means the relative environmental impacts needed to be treat more important.

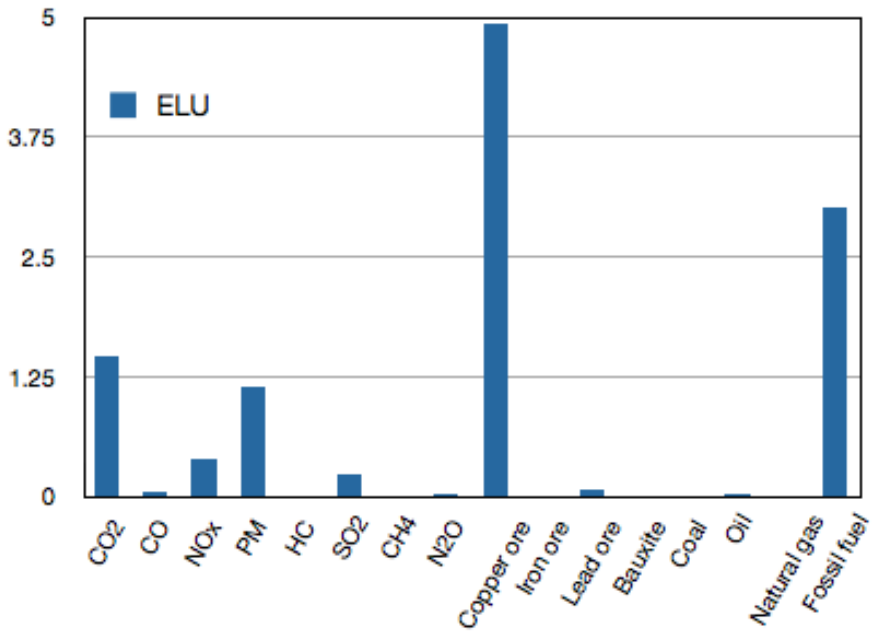

Figure 55. Main indices for environmental impact assessment with the EPS 2000-method over the entire life cycle

- According to the EPS 2000-method, the demand of copper ore is the most important parameter that weights extremely heavy. As it is noticed, since the demand of copper ore only appear in electricity production, the process with relatively big electricity demand naturally weights heavily.
- The use of fossil fuel is also very important parameter, and the method highlights the parameter of CO_2 emission as well, but it gives less weight on emission of NO_x.

5.4.2 Distance-to-target

The third method is according to a principle known as distance-to-target, where the severity of the impact is determined by the quotient between the current levels of emissions within certain geographical area and the level that is treated as crucial, i.e.

the target level (Bengtsson and Steen 2000). In reality, the definition or determination of the target level is usually influenced by the public policy goals.

EDIP

For the EDIP method, the Danish policy targets are centered the weighting step and the weighting is done in three separate categories- environmental impacts, resource consumption and impacts on working environment (Baumann and Tillman 2004). Since the three categories are modeled separately and not aggregated, in the case presented in this thesis, it is chosen to aggregate both emissions and resources.

The weighting indices of EDIP used in this study is according to (Henrik and Hauschild 1998), and the weighting results of using EDIP for assessing the environmental impact of each life cycle is illustrated in figure 5.6.

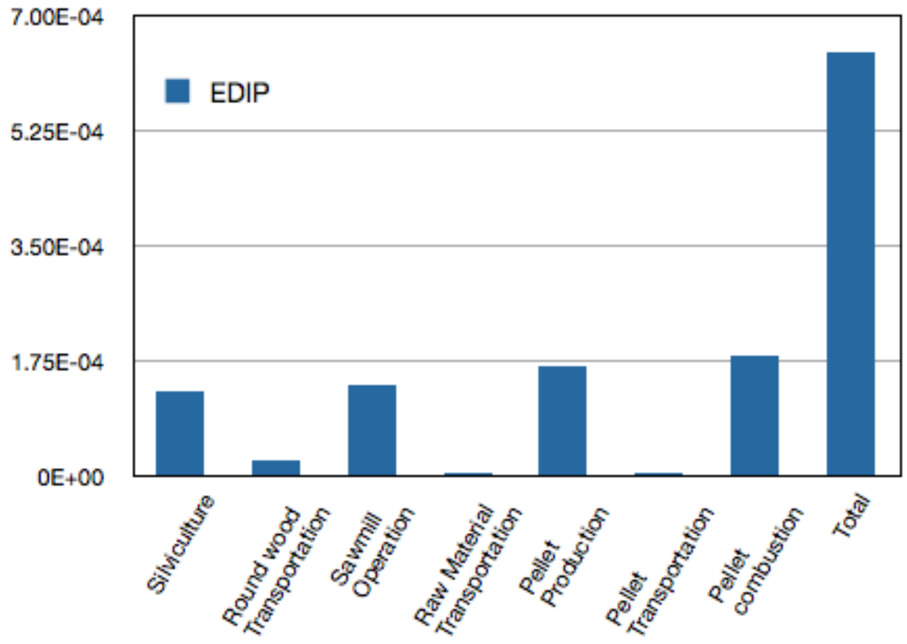

Figure 5.6. Environmental impact assessed with the EDIP-method

The result of the EDIP-method gives a little different picture with EPS2000.

- Except the transportation process, the importance of the environmental impacts in relation to the Silviculture, Sawmill Operation, Pellet Production and Pellet Combustion is almost equal.
- The environmental impacts associated with Pellet Combustion are still the most significant, followed by the Pellet Production, Sawmill Operation and Silviculture.
- To have the same trait with EPS2000, the process with big electricity demand weights heavily in EDIP-method.

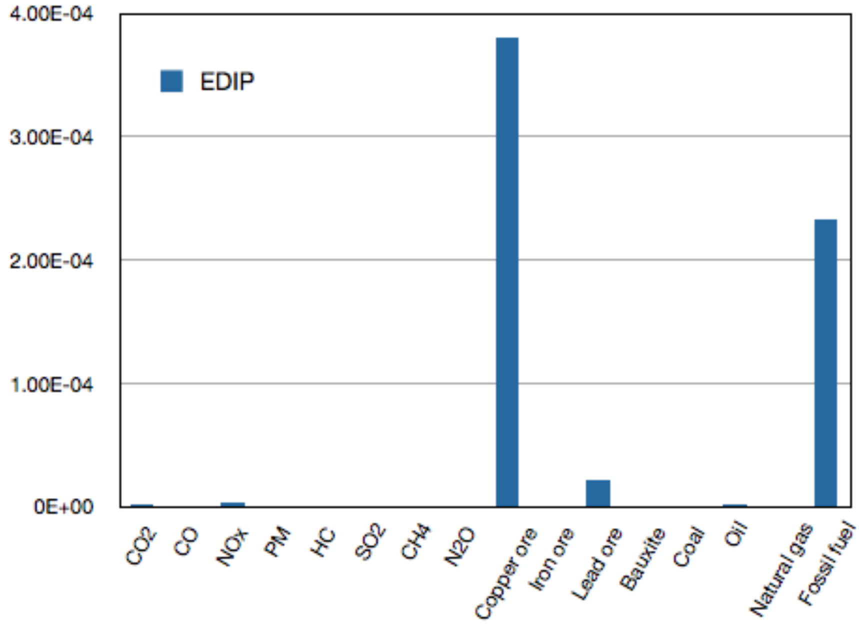

Figure 5.7. Main indices for environmental impact assessment with EDIP-method over the entire life cycle

- It is extremely obvious that the EDIP-method highlights the depletion of copper ore and the use of fossil fuel.
- On the other hand, the method weights other parameters, especially the parameters regarding the emission to the air and water, lightly, which also reflect a fact that the damage-oriented methods have a comparatively even contribution of the overall weight, whereas the distance-to-target methods tend to put more weights on issues of great future significance, i.e. depletion of mineral and fossil resources.

6 Conclusion and recommendation

The study of this project covered the whole life cycle of wood pellets production, aiming at assessing its environmental performance. Comparing with other industrial products, whose manufacturing processes are much complicated, the processes for wood pellets production are fairly simple and straightforward. Plus the raw materials for wood pellet are only sawdust, and sometimes wood chips, which are all byproducts from the production of sawn wood. Therefore the project was rather small enough that only a number of common parameters could be chosen to measure, mainly regarding emissions to the air and resources depletion, compared with many other LCAs, which sometimes include hundreds of parameters.

6.1 General conclusion

The conclusion is about to answer the questions proposed in section 3.1, which will base on the results come out of inventory analysis and environmental impact assessment. The results are interpreted in different level of details, which will probably support the conclusion from different perspectives.

According to the results of inventory analysis:

- The Silviculture is the biggest CO_2 contributor of the entire life cycles. The emission of CO_2 has very direct relationship of consuming fossil fuel in this case, since the combustion of biofuel is free of CO_2, there is not other obvious CO_2 sources but the consumption of fossil fuels. Therefore it is fairly reasonable to attribute the big emission of CO_2 at Silviculture to the extensively use of fossil fuel-driven machines.
- The Pellet Combustion process dominants most of the emissions to the air and water, which makes it the least environmental friendly process if only from the perspective of inventory data.
- The Pellet Production process has remarkably high emission of HC, which could be result from the incomplete of biofules. Moreover the Pellet Production process is also the most energy intense process, where a large quantity of energy is used for drying the wet sawdust, comminuting sawdust and pelleting sawdust into wood pellets. The energy used in this step roughly equals to 17% of the energy contained in the wood pellets delivered to the customers.
- The demand of natural resources (except wood) in this project is mainly originated from the production of electricity. Therefore the processes with relatively more electricity requirement naturally consume more natural resources.

When it comes to characterization level, the inventory results are aggregated and translated into real environmental impacts.

- There are at least six potential environmental impacts that can be possibly related to wood pellets industry, including global warming, acidification, eutrophication, photochemical oxidant formation, human toxicity and resource depletion, which can be attributed to the emission of carbon dioxide, carbon monoxide, nitrogen oxides, particulate matters, hydrocarbon, sulfur dioxide, methane, nitrous oxide and depletion of fossil fuels.
- Silviculture is with the biggest global warming potential in the entire life cycles, followed by Round Wood Transportation, and is neglect in the rest of the life cycle processes. The global warming potential has quite obvious relationship with the consumption of fossil fuel in this project. Consuming fossil fuel is the main reason to initiate global warming potential in the life cycles of wood pellet production.
- Pellet Combustion is the process with the biggest human toxicity potential, eutrophication potential and photochemical oxidant potential. This is because this process has the largest emissions to the environment, especially dominants the emissions of PM, CO, NO_x, CH_4, N-tot that will probably initiate the environmental impacts.
- Pellet Production has very slight contribution to all the six potential environmental impacts.
- The processes with big depletion of fossil resource give rise to relatively high potential of resource depletion.

Three valuation methods are used to weigh the severity of the environmental impact over each life cycle process. Although to some extent, the three methods tend to weigh the impact different from one to another, some results are similar.

- The depletion of fossil fuel is the most significant parameter, since it has been weighted heavily in all the three valuation methods. In addition to depletion of fossil fuel, different valuation method tends to highlight different parameters. The damage-oriented methods have a comparatively even contribution of the overall weight, whereas the distance-to-target methods tend to put more weights on issues of great future significance, i.e. depletion of mineral and fossil resources
- The environmental impact of Pellet Combustion step dominates over the impact of the entire life cycle of producing wood pellets. Although this step is fossil fuel free, it produces a mass of different kind of emissions to the air, and the quantity of electricity consumed for the pellet burners to ignition and automatically feeding is also outweigh the rest of life cycles, which makes it the least environmental friendly process weighted by all the three valuation methods.

- The EPS2000 and EDIP-method weights very heavily of the depletion of copper ore, which only appears in producing electricity, and the electricity consumption of Pellet Production process is fairly big, which makes it not very environmental preferable compared with the rest of the life cycle processes. However, if depletion of mineral resources is not weighted that heavy, the environmental impacts associated with Pellet Production are not very significant, as it is shown in Ecoindicator'99-method.

6.2 Sensitivity analysis

Sensitivity analysis on transportation

Since the use of fossil fuel is the most significant factor in triggering environmental impacts, a sensitivity analysis is made to see how big difference it will be, if some improvements are made at this point.

To maintain the rest conditions, then to upgrade all the vehicles' engines for transportation to fulfill the EU emission standard class Ⅳ and Ⅴ respectively, in comparing the present situation. The results are shown in Table 6.1.

Table 6.1 The results of sensitivity analysis on transportation

	Reference scenario	EuroIV	Euro V
Energy (MJ)	31.8	28.7	28.7
CO_2 (kg)	2.37	2.12	2.12
CO (g)	3.27	2.31	2.29
NO_x (g)	15.9	10.6	5.6
Particles (g)	0.268	0.0795	0.0775
HC (g)	1.043	1.024	1.018
CH_4 (g)	0.0250	0.0246	0.0244
SO_2 (g)	0.0120	0.0107	0.0107
N_2O (g)	0.0171	0.0152	0.0147

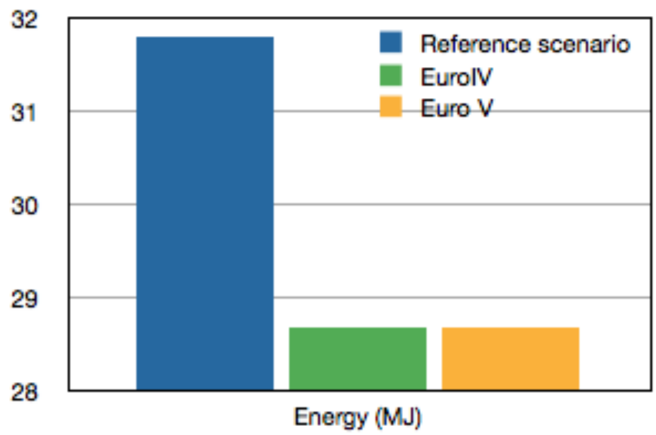

Figure 6.1. Energy use for upgrading vehicle engine - sensitivity analysis

Figure 6.1 illustrates that it will save about 3.1MJ on transporting, which roughly equals to 0.087 liter of fuels, if the energy content of the fuel is 35.8MJ/L (*www.spi.se*). But there is no big difference on energy consumption if the vehicle engine is upgraded to EU Ⅳ or EU Ⅴ.

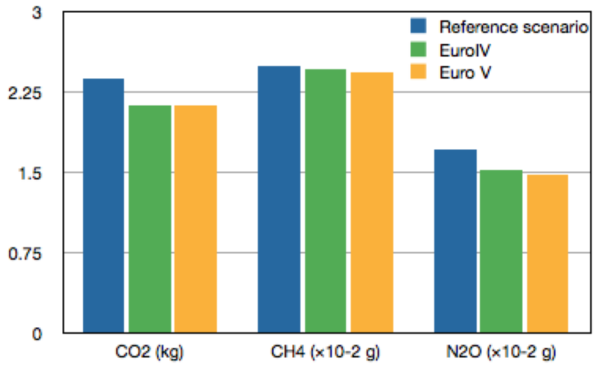

Figure 6.2. GHG emission for upgrading vehicle engine - sensitivity analysis

The change of GHG emissions in upgrading vehicle engines is shown in figure 6.2. The upgrading reduced about 0.25kg of CO_2 emission just in the process of transportation.

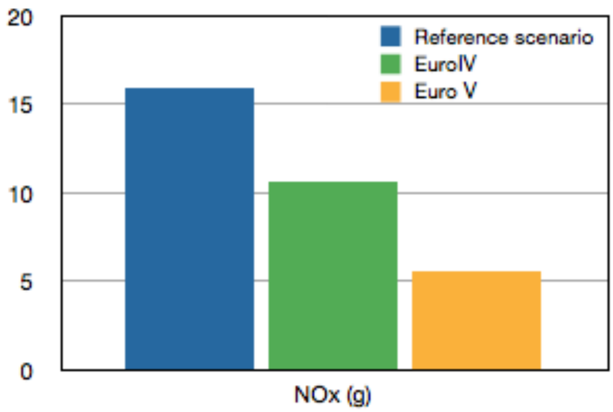

Figure 6.3. NO_x emission for upgrading vehicle engine - sensitivity analysis

The most significant improvement in upgrade vehicle engine to EU Ⅳ or Ⅴ standard comes from the reduction of NO_x emission, which can be seen in figure 6.3. Considering NO_x has big influence on eutrophication and acidification, in some degree, this upgrade will probably have positive effect on reducing such environmental impacts.

Sensitivity analysis on small-scale wood pellet burners

Due to the reason that a variety of small-scale wood pellet burners with combustion efficiencies ranging from 50% to more than 80% are available in the market, the emissions of burning wood pellets are to a large extent depending on what kind of burners people installed. Therefore a sensitivity analysis is made on this part, in order to find out how big influence of using different burners to the emissions of combusting wood pellets.

The analysis is made by setting a reference scenario, which in this case is the most common installed wood pellet burner for Swedish context (the output power is 11kW with the net efficiency 78%), and another three scenarios, whose burners share the same output power but with the efficiency of 85% (scenario 1), 70% (scenario 2) and 50% (scenario 3) respectively. The modeling is using the same LCA software GEMIS4.5 as it is used in the inventory analysis. The results are shown in Table 6.2.

Table 6.2 Results of sensitivity analysis on small-scale burners

	Scenario 1 (85%)	Reference scenario (78% efficiency)	Scenario 2 (70%)	Scenario 3 (50%)
Pellet (kg)	23.3	25.4	28.3	39.7
CO (g)	24.8	26.9	29.6	40.5
CH_4 (g)	2.4	2.5	2.7	3.4
N_2O (g)	0.5	0.5	0.5	0.8
PM (g)	6.4	6.9	7.7	10.7
NO_x (g)	27.9	30.4	33.8	47.0
SO_2 (g)	12.3	13.4	14.9	20.7
Heat (kWh)	84.96	84.96	84.96	84.96

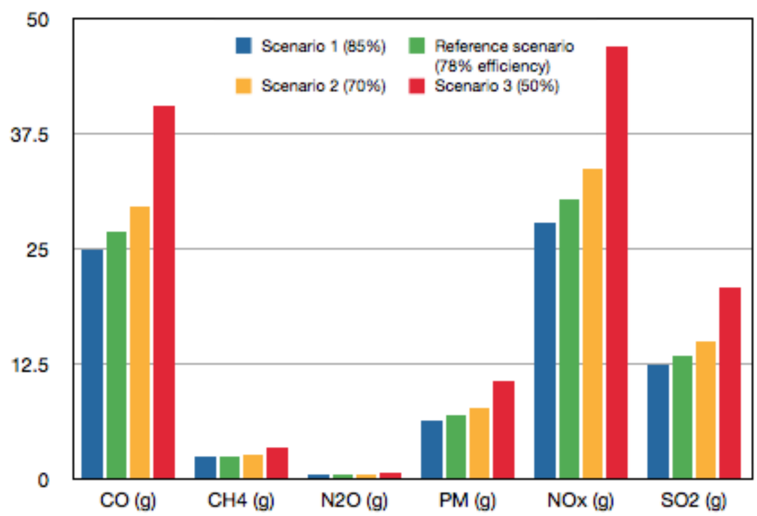

Figure 6.4 Emissions for using different efficiency wood pellet burners at small-sale customers' – sensitivity anal

According to Figure 6.4, it is clear that the efficiency of the burner has great influence on the combustion emissions. A high efficiency pellet burner produces less emissions and thus is more environment preferable.

6.3 Recommendation

Several recommendations are given in this section, in order to help improve the environmental performance of the wood pellets.

1. Since the depletion of fossil fuels is the hot point in this study, it is important to point out that to cut off the use of fossil fuels will absolutely reduce the environmental impacts that associated with the wood pellet industry. Considering the use of fossil fuel, such improvement could be done by performing a good management on logistics, which includes a good mapping of transporting route and a good choice of tools for transportation, such as to use train for long distance transportation instead of trucks, or to upgrade the trucks to fulfill the higher EU emission standards for transportation. In addition to the possible improvement on transportation, other possibility include for example, to encourage the use of biofuels to replace fossil fuel, or in silviculture step, to use motor-manual felling replace the mechanized felling, which has been proved would have much lower emission levels (Berg 1997).

2. In the pellet plant, when sawdust is compressed into wood pellets, a large amount of energy is consumed on drying and compressing, which makes it the most energy intense process in the entire life cycle. But in the mean time, a certain quantity of energy is wasted in forms of high temperature water vapor. Though the energy is mainly from burning biofuels, which has fairly small environmental concerns, to have this part of energy recycled will increase the efficiency of energy usage, which will help to reduce the cost of the company and also preferable for the environment. However, to have such improvement will probably include further investment on changing the present technique or even the layout of the factory. A brief discussion will be made in section 7.3 on this part.

3. Even though it is not include in the project, there are other environmental problems in relation to the wood pellet production have to be counteracted by, for example, preventing emissions. Lending credence to my position is the substance monoterpenes that has been mentioned to have 69% or even more released in the process of drying (Ståhl and Berghel 2008). Although it has not been included in the inventory analysis due to lack of data, it has effects on human health and the formation of photo oxidants. However, the emission of monoterpenes can be reduced by means of conditioning the dryers to run under certain temperature and residence time. Furthermore, since the residence time of the dried material as well as the initial drying medium temperature have great influence on the emission of monoterpenes from wood, a better choice of drying technology also has positive effect on restricting monoterpenes emission.

4. Regarding the pellet burners, the amount of emissions from burning wood pellets depends on the efficiency of the burners. High efficiency burners are always favorable since it produces less emissions to the air, and thus more environmental friendly. Additionally, the pellet burners consume electricity in order to automatically feed wood pellets into the burner and ignition. However, the environmental impact associated with electricity production in this project is weighted heavily. Therefore the environment will benefit from saving use of electricity.

7. Discussion

7.1 Carbon dioxide emission over time

Worldwide the concern of global warming is growing day by day since many of the consequences caused by global warming are devastating. Global warming is originally initiated by emitting green house gas (GHG), especially the emission of carbon dioxide. The effect of green house gas (e.g. carbon dioxide) in the atmosphere is to absorb the radioactive force emitted from the ground and then heat the Earth. A brief discussion is given here to discuss the nature of carbon dioxide emission from biomass-based product in certain time horizons, but beware that such discussion is not aimed at making any suggestions on how to account for carbon dioxide in LCA study, but more like an explanation that why the emission of carbon dioxide in burning bio fuel is not included in the life cycle inventory analysis.

It is not uncommon that in LCAs the emitted carbon dioxide from all concerned materials and processes needs to be taken into consideration. However, when it comes to bioenergy system or any wood-related products, the situation is a little different.

Either forests or crops will absorb carbon dioxide in order to start photosynthesis to form carbohydrate and release oxygen during their growth. Such carbon dioxide is considered to be stored, and therefore living biomass is regarded as a carbon dioxide stock. Whether the absorption of carbon dioxide during the growth of the plants needed to be accounted in LCI is a touchy issue that has been debating for many years. It is argued that if the carbon dioxide absorbed in plants is accounted, then the analysis must include the carbon dioxide emitted from burning biomass as well (Yaros and Boustead 1994). However, in most LCAs only carbon dioxide emitted from using fossil fuels are included, while emissions regarding the consumption of renewable fuels are not accounted, since the net carbon dioxide flow from bioenergy system to the atmosphere is determined only by the fossil fuel input and how the biomass harvesting affect the general biological carbon stock (Gustavsson and Karlsson 2001). Carbon dioxide stock will not decrease if the biomass regrows continuously to compensate the loss due to burning, which is also the prerequisite of keeping the carbon dioxide emissions excluding from an LCA study, when biofuels are used for energy purpose.

In one word, if the wood-related product has a relatively short lifetime (e.g. wood pellets, food products, paper or other biofuels etc.), the stored carbon dioxide will be soon released, and close the carbon recycling cycle without releasing additional carbon dioxide in the atmosphere. In such circumstance, it is fairly reasonable to omit carbon dioxide emissions in an LCA. However, it is not the case if the lifetime of the product is long, for example if the product is wooden furniture, whose lifetime could be decades, then such omission should be avoided.

7.2 Comparison of avoided GHG emissions from using different kinds of wood energy

Many studies have proved the fact that in general, the use of wood products instead of other materials will cause less green house gas emissions. Indeed, to facilitate the use of biofuels to substitute energy-intensive materials or traditional fossil fuels has long-term effect on avoiding green house gas emission. Therefore wood products, either from barks to sawdust or any other processed biomass fuels (wood pellets and briquettes for example), are become more and more popular. Like in this project, a large amount of biofuels, such as barks, wood chips, waste wood, are also used, which give birth to an interesting topic that how the use of different kind of biofuels avoided GHG emissions. The purpose of this discussion is not about to give out the detailed sensitivity analysis process, but some general results made by former researches are collected and presented here. The comparison is made by using wood-related fuels (wood pellets, briquettes, barks, sawdust and fuel wood) to replace oil or electricity.

According to Peterson Raymer (2006), first consider the situation that one cubic meter timber is used to produce different biofuels, whose energy will be used to substitute either oil or electricity. This substitution will avoid GHG emissions ranged from 0.28 to 0.47 tone CO_2-equivalents (Petersen and Ann 2006). Wood pellets and briquettes have the biggest avoided emissions, followed by sawdust and fuel wood when the energy substitutes oil, barks and fuel wood when the energy substitutes electricity (Petersen Raymer 2006). The reason why fuel wood substitutes heating oil avoids more GHG emissions than it substitutes electricity, is probably because the burning equipments in generating electricity (coal-fired power plants for instance) are always more efficient than oil-burning equipments (domestic stoves for instance). This indicates that the efficiency of the burning equipments sometimes has big influence on avoiding GHG emission. Lending credence to this is that a well-designed wood pellets boiler will enhance the ability of avoiding emissions by 17%, compared with large combustion facilities (Petersen Raymer 2006).

Second, when 1GWh energy is produced from the wood-related biofuels, the avoided GHG emissions will range from 240 to 340 ton CO_2-equivalents (Petersen and Ann 2006). The ranking for avoided emissions is that fuel wood substituting oil followed by sawdust, bark, wood pellets, briquettes and fuel wood substituting electricity at last (Petersen Raymer 2006). As it is quite obvious that such raking is different from the one that avoided GHG emissions per cubic meter wood. This is probably because wood pellets and briquettes have relatively high energy content that is able to give more energy than barks or sawdust per unit volume and considering the avoided GHG emissions per GWh equals to the avoided GHG emissions per cubic meter divided by the total energy produced by the wood product. Therefore the bigger energy content of the wood product, the less avoided GHG emissions it made.

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Appendix I. Recirculation of discharged drying gases

As it is mentioned before, drying is an energy intense process, which takes about 10%-12% of the heating value of wood pellets. For a pellet plant, which uses flue gasses as a heating medium, it is always facing a dilemma on how to deal with the discharged drying gases. On one hand, with the discharged drying gases, a part of energy is wasted in forms of heat. To recirculate the discharged drying gases will probably improve the energy efficiency and thus save energy. On the other hand, to introduce the energy recycling technology always means further investment, which in certain circumstance is huge.

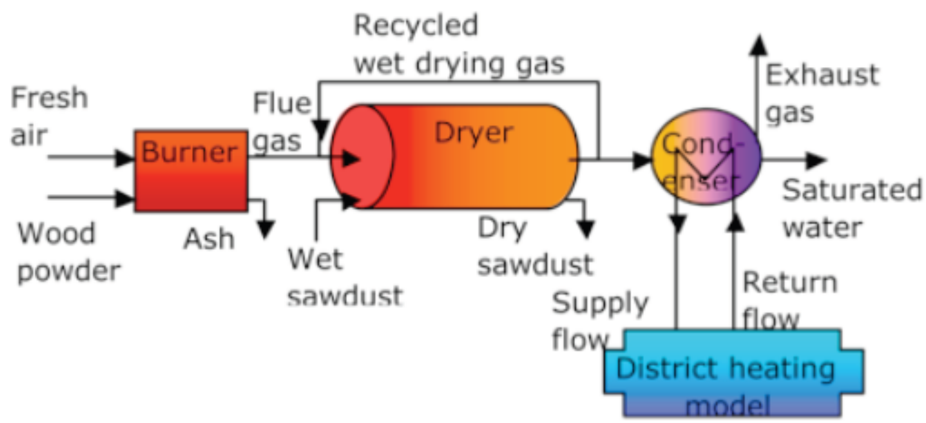

Figure 1 A schematic sketch of drying equipment with recirculation of drying gases (Ståhl and Berghel 2008)

Figure 1 shows a drying system with the recirculation equipment for recirculating drying gases and energy recovery over a condenser. Compared with the drying system that Neova adopted, which is without recirculation equipment, this system includes four main part: a burner used for burning fuels and providing flue gas; a direct heated dryer for drying sawdust; a condenser for recovering energy; and a district heating model, which is a model used for estimating the regained energy over the condenser. The recovering process is following the thermodynamic law that is not going to specify here, but some results of formers studies are chosen to present here.

According to Ståhl and Berghel 2008, the recirculation helps to improve the drying efficiency. When increase the ratio of drying gases recirculation, the operation of the dryer becomes more energy efficient, and in the meantime the dew point of the gases out of the dryer goes up quickly, which makes the condenser able to recover energy even more, which in turn imply the district heating grids are able to receive more energy from the condenser.

The results of Ståhl's research are illustrated in Figure 2 and 3. He made a comparison of the scenarios with different recirculating rate of gas flow to the one without recirculation of drying gases. In Figure 2, EM is the benchmark scenario that has not implemented the drying gases recirculating system, which is similar to the Neova's situation, whereas S1, S2, S3 are the scenarios with recirculation rate from 30% to 50% and 65% respectively. It is quite clear that the scenarios with implemented drying gases recirculation process saved energy, and it is a lot better to recirculate drying gases than not to. From Figure 3, it is also clear that to have drying gases recycled will help to increase the dryer efficiency as well.

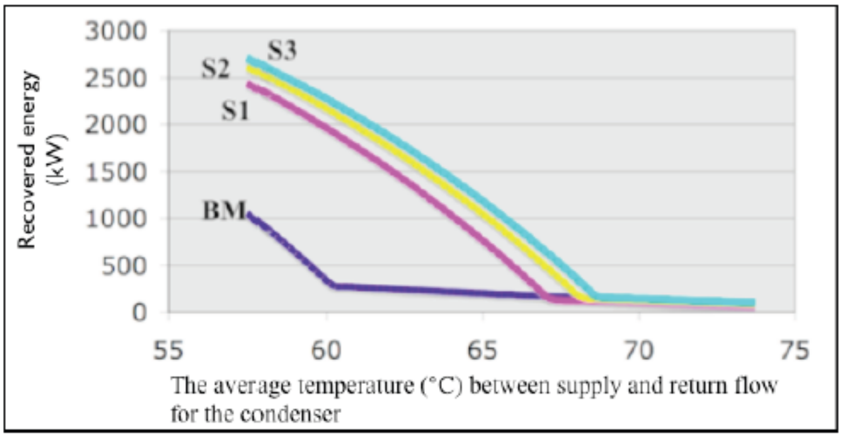

Figure 2. Recovered energy as a function of the average temperature between supply and return flow over a condenser due to increasing drying gas recirculation (Ståhl and Berghel 2008)

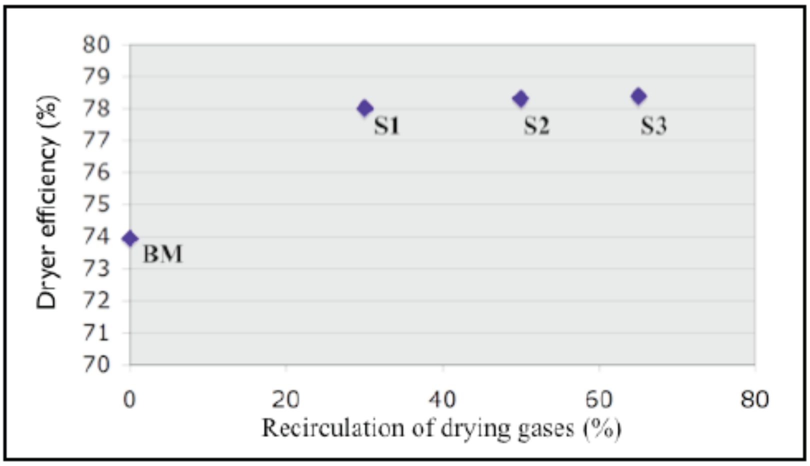

Figure 3. The change in dryer efficiency as a function of the recirculation of drying gases (Ståhl and Berghel 2008)

Appendix Ⅱ. Life Cycle Inventory Data

Silviculture

Activity: Silviculture	Data as collected	Normalized to activity	Linked flow Normalized to F.U	Flows passing system boundary, Normalized to F.U.
Inflow:				
Diesel (MJ)	153	153		130
Electricity (kWh)	0.092	0.09		0.08
Forest land (ha)	0.0025	0.003		0.003
Gasoline (MJ)	0.98	0.98		0.8
HDPE (kg)	0.0075	0.008		0.007
Kerosene (MJ)	1.08	1.1		0.9
Nitrogen fertilizer (kg)	0.38	0.4		0.3
Peat (kg)	0.09	0.1		0.09
Thinned forest area (ha)	0.0025	0.003		0.003
Tree seeds (kg)	0.0015	0.002		0.002
	155.06			
Outflow:				
Timbers (m^3 s.u.b.)	1	1	0.85	
forest land(ha)	0.0025	0.003		0.003
Carbon monoxide (CO) (g/ m^3 s.u.b)	2.01578	2.0		1.7
Hydrocarbons (HC) (g/m^3 s.u.b)	2.79108	2.8		2.4
Methane (CH_4) (g/m^3 s.u.b)	1.01	1.01		0.9
Dinitrogen oxide (N_2O) (g/m^3 s.u.b)	0.879	0.9		0.8
Nitrogen oxides (NO_x) (g/m^3 s.u.b)	23.259	23.3		20
Particles (g/ m^3 s.u.b)	4.6518	4.7		4.0
Sulphur oxides (e.g. SO_2) (g/ m^3 s.u.b)	60.4734	60.5		51.4
Carbon dioxide (CO_2) (g/ m^3 s.u.b)	12404.8	12405		10,567

Sawmill operation:

Before allocation:

Activity: Sawmill operation	Data as collected	Normalized with sawdust	Linked flow, normalized to F.U	Flows passing system boundary normalized to F.U. (Unallocated)
Inflow:				
Timber m sut	2091200	2.2674	0.8519	
Electricity, kWh	62900000	68.1991		25.6224
Thermal energy MJ	1561320000	1692.9		636
Bio-fuel [a], m^3	294800	0.3		0.1
Bio-fuel, MJ	742896000	805.5		302.6
Solid energy, MJ	50760000	55		20.7
Outflows				
Timber products, m^3	993299	1.1		0.4
Pulp chips, m^3s	1735700	1.9		0.77
Dry chips, m^3s	336200	0.4		0.17
Sawdust, m^3s	922300	1.00	0.4	
Bark, m^3s	529700	0.6	0.2	
NOx g	103200000	111.9		427
CO_2 g	4305000000	4667.7		1753.7
Ash, m^3	2647	0.003		0.002
Hazardous waste, g	21000000	22.8		8.6
Other waste, g	193000000	209.3		78.6
SO_2	22286880	24.2		9.1
CO g	742896000	805.5		302.6
HC g	74289600	80.5		30.3

a. Energy density of bioenergy: 2800MJ/m^3. Energy efficiency: 90%.

Allocation factors based on relative volume and economic value:

	Market price (SEK/CUM) [a]	Volume (m^3)	Total economic value	Allocation factor（volume)	Allocation factor（price)
Sawlogs	390	0.4046	157.8024	0.2199	0.3888
Pulpwood	230	0.7070	162.6191	0.3842	0.4007
Sawdust	120	0.3757	45.0840	0.2042	0.1111
barks	130	0.2158	28.0506	0.1173	0.0691
Wood chips	90	0.1370	12.3256	0.0744	0.0304

a. Market price according to (Lundmark 2006)

Allocation based on three allocation approaches:

Aggregated over system	Flows passing system boundary; UNAILOCATED	Allocated based on relative volume	Allocated all to sawn timber	Allocated based on market price
Electricity use at the sawmill				
Sawn timber	25.6	5.6	25.6	10.0
Pulp chips		9.8	0	10.3
Sawdust		5.2	0	2.8
Bark		3.0	0	1.8
Chip		1.9	0	0.8
Thermal energy use at the sawmill				
Sawn timber	636.0	139.9	176.7	247.3
Pulp chips		244.4	0	254.8
Sawdust		129.9	0	70.6
Bark		74.6	0	44.0
Chip		47.3	0	19.3
Bio-fuel use at the sawmill				
Sawn timber	0.1	0.03	0.1	0.05
Pulp chips		0.05	0	0.05
Sawdust		0.02	0	0.01
Bark		0.01	0	0.008
Chip		0.01	0	0.004
Bio-fuel use at the sawmill				
Sawn timber	302.6	66.5	302.6	117.7
Pulp chips		116.3	0	121.2
Sawdust		61.8	0	33.6
Bark		35.5	0	20.9
Chip		22.5	0	9.2
Solid energy use at the sawmill				
Sawn timber	20.7	4.5	5.7	8.0
Pulp chips		7.9	0	8.3
Sawdust		4.2	0	2.3
Bark		2.4	0	1.4
Chip		1.5	0	0.6
CO_2 emissions at the sawmill				
Sawn timber	1753.6	385.6	1753.6	681.8
pulp chips		673.8	0	702.6
Sawdust		358.1	0	194.8
Bark		205.6	0	121.2
Chip		130.5	0	53.3
NO emissions at the sawmill				
Sawn timber	42.0	9.2	42.0	16.3
pulp chips		16.2	0	16.8
Sawdust		8.6	0	4.7
Bark		4.9	0	2.9
Chip		3.1	0	1.3

SO_2 emission at the sawmill				
Sawn timber	9.1	2.0	9.1	3.5
pulp chips		3.5	0	3.6
Sawdust		1.9	0	1.0
Bark		1.1	0	0.6
Chip		0.7	0	0.3
CO emission at the sawmill				
Sawn timber	302.6	66.5	302.6	117.7
pulp chips		116.3	0	121.2
Sawdust		61.8	0	33.6
Bark		35.5	0	20.9
Chip		22.5	0	9.2
HC emission at the sawmill				
Sawn timber	30.3	6.7	30.3	11.8
pulp chips		11.6	0	12.1
Sawdust		6.2	0	3.4
Bark		3.5	0	2.1
Chip		2.3	0	0.9
Ash emissions at the sawmill				
Sawn timber	0.001	0.0002	0.001	0.0004
pulp chips		0.0004	0	0.0004
Sawdust		0.0002	0	0.0001
Bark		0.0001	0	0.00007
Chip		0.00008	0	0.00003
Hazardous waste at the sawmill				
Sawn timber	8.6	1.9	8.6	3.3
pulp chips		3.3	0	3.4
Sawdust		1.7	0	1.0
Bark		1.0	0	0.6
Chip		0.6	0	0.3
Other waste at the sawmill				
Sawn timber	78.6	17.3	78.6	30.6
pulp chips		30.2	0	31.5
Sawdust		16.1	0	8.7
Bark		9.2	0	5.4
Chip		5.9	0	2.4

Environmental load allocated to sawdust:

Product: Sawdust	Flows passing system boundary normalized to F.U. (Unallocated)	Allocated based on relative economic value (g/0.3757 m³ sawdust)	Linked flow Normalized to F.U (based on economic value)
Inflow:			
Timber m^3 sut	0.9	0.9	0.9
Electricity, kWh	25.6	2.8	2.8
Thermal energy MJ	636	70.6	70.6
Bio-fuel, m^3	0.12	0.013	0.013
Bio-fuel, MJ	742896000	33.6	33.6
Solid energy, MJ	20.7	2.3	2.3
Outflows			
Sawdust (m^3)	0.4	0.4	0.4
NO_x g	42	4.7	4.7
CO_2 g	1753.6	194.8	194.8
SO_2 g	9.1	1.0	1.0
CO g	302.6	33.6	33.6
HC g	30.3	3.36	3.36
Ash, m^3	0.001	0.0001	0.0001
Hazardous waste, g	8.6	0.95	0.95
Other waste, g	78.6	8.7	8.7

Environmental load allocated to barks:

Product: Bark	Flows passing system boundary normalized to F.U. (Unallocated)	Allocated based on relative economic value (g/0.3757 m³ sawdust)	Linked flow Normalized to F.U (based on economic value)
Inflow:			
Timber m^3 sut	0.9		
Electricity, kWh	25.6	1.8	0.54
Thermal energy MJ	636.0	44	13
Bio-fuel, m^3	0.1	0.008	0.002
Bio-fuel, MJ	742896000.	20.9	6.3
Solid energy, MJ	20.7	1.4	0.4
Heating oil WRD, m^3			0
Outflows			0
NO_x g	42	2.9	0.9
CO_2 g	1753.6	121.2	36.4
SO_2 g	9.1	0.6	0.2
CO g	302.6	20.9	6.3
HC g	30.3	2.1	0.6
Ash, m^3	0.001	0.00007	0.00002
Hazardous waste, g	8.6	0.6	0.2
Other waste, g	78.6	5.4	1.6
Bark (m^3)	0.2	0.2	0.06

Pellet production

Activity: Pellet production	Data as collected	Normalized per activity	Linked flows, normalized to F.U.	Flows passing system boundary, normalized to F.U.
Inflows				
Sawdust (m3) (consumption)	585000	6.5	0.7	
Barks (m3) [a]	90000	1.0		0.1
Barks (MJ)	212,544,000	2361.6		236.2
Electricity (KWh)	14580000	162.0		16.2
Diesels (MJ) [b] (81m3)	2849442	31.7		3.2
Outflows				
Pellets (ton)	90000	1.0	0.1	
NO_x (g)	28625526	318.1		31.8
Particulates (g)	49560	0.6		0.06
CO (g)	39380255	437.6		43.8
CO_2 (g)	208056851	2311.7		231.2
SO_2 (g)	617677	6.9		0.7
HC (g)	21,398,600	237.8		23.8
Terpenes (g)	38000000	422.2		42.2
Ash	16,365,888	181.8		18.2

(a). Barks: Energy density 2620 MJ/m3
Bulk density: 320 kg/m3
Moisture content: 50%
NCV: 8.2 MJ/kg
Source: (Loo and Koppejan 2008)

(b), Diesel: Thermal value: 43.43 MJ/kg
Density: 0.81 kg/l
Source: CPM database

Pellet combustion

Large-scale pellet combustion plant

Activity: Large-scale pellet combustion plant	Data as collected	Normalized per activity	Linked flow, Normalized to F.U.	Flows passing system boundary, Normalized to F.U.
Inflows (36% produced pellets coming in)				
Pellet (g)	265	265	20808	
Degreasing compound (g)	0.000446	0.0004		0.04
Electricity (kWh)	0.0744	0.07		5.8
Hydrazine (g)	0.00223	0.002		0.2
Lubricating oil (g)	0.00223	0.002		0.2
Outflows				
Heat (kWh)	1	1		78.5
CO (g)	0.406	0.4		31.9
CO_2 (g)	445	445		34942
PM (g)	0.00442	0.004		0.3
NO_x (g)	0.243	0.2		19.1
Ashes (g)	6.21	6.2	488	
Ion exchanger (g)	0.00223	0.002		0.2
Waste (g)	0.208	0.2		16.3
Waste oil (g)	0.0223	0.02		1.8

Mid-scale pellet combustion plant

Activity: Mid-scale customer	Data as collected	Normalized per activity	Linked flow, Normalized to F.U.	Flows passing system boundary, Normalized to F.U.
Inflows (20% produced pellets coming in)				
Pellet (g)	225	225	11560	
Electricity (kWh)	0.06	0.1		3.08
Outflows				
CO (g)	0.288	0.3		14.8
CO_2 (g)	438	438		22503.5
PM (g)	0.149	0.1		7.7
NO_x (g)	0.376	0.4		19.3
SO_2 (g)	0.04	0.0		2.1
Heat (kWh)	1	1		51.4
Ash (g)	5.78	5.8	297	

Small-scale pellet stoves

Activity: Small-scale customer	Data as collected	Normalized per activity	Linked flow, Normalized to F.U.	Flows passing System boundary, Normalized to F.U.
Inflows (44% produced pellets coming in)				
Pellet (g)	83149000	299.3	25432	
Electricity (kWh)	4200	0.02		1.7
Outflows		0		0.0
CO (g)	87798.825	0.3		25.5
CH4	8214.6468	0.03		2.5
N_2O	1615.2092	0.006		0.5
PM	22696.620	0.08		6.8
NO_x (g)	99251.862	0.4		34.0
SO_2 (g)	43792.576	0.2		17.0
Ash (g)	746766.16	2.7		229.4
Heat (kWh)	277777.8	1		85

Transportation

Emission factors for transportation based on euro engine class (NTM, Bäckström 2007,)

	Truck with draw bar trailer			
	Euro 2	Euro 3	Euro 4	Euro 5
Energy(MJ/ ton*km)	0.43676	0.43676	0.43676	0.43676
CO_2 (g/ton*km)	32.3	32.3	32.3	32.3
CO (g/ton*km)	0.0448	0.0538	0.0351	0.0348
NO_x (g/ton*km)	0.392	0.27	0.162	0.0852
PM (g/ton*km)	0.00575	0.00604	0.00121	0.00118
HC (g/ton*km)	0.014	0.0128	0.0156	0.0155
CH_4 (g/ton*km)	0.000337	0.000306	0.000374	0.000371
SO_2 (g/ton*km)	0.000163	0.000163	0.000163	0.000163
N_2O (g/ton*km)	0.000361	0.000234	0.000231	0.000224

Wood pellet distribution [a]

Activity: Transportation (pellet plant to customers)	Data as collected	Normalized per activity	Linked flows, normalized to F.U.	Flows passing system boundary, normalized to F.U.
Inflows				
Wood pellet (ton)	90000	1	0.0578	
Energy (MJ)	6,192,602.7	68.8		3.98
Outflows				
wood pellet (ton)	90000	1	0.0578	
CO_2 (g)	493,602,786	5,484.5		317.
CO (g)	684,586.2	7.6		0.4
NO_x (g)	3,372,663	37.5		2.2
PM (g)	58,373	0.6		0.04
HC (g)	215,918.6	2.4		0.14
CH_4 (g)	5,170	0.06		0.003
SO_2 (g)	2,491	0.03		0.002
N_2O (g)	3,643	0.04		0.002

a. Distance: 165 km to small-scale customers
180 km to Mid-scale customers
170 km

Round wood transportation [a]

Activity: Transportation (round wood to sawmill)	Data as collected	Normalized per activity	Linked flows, normalized to F.U.	Flows passing system boundary, normalized to F.U.
Inflows				
Round wood [b] (m^3)	1	1	0.8519	
Energy (MJ)	27.1	27.1		23.1
Outflows				
Sawlog (m^3)	1	1	0.8519	
CO_2 (g)	2002.6	2002.6		1,706
CO (g)	2.8	2.8		2.3
NO_x (g)	13.4	13.4		11.4
PM (g)	0.2	0.2		0.2
HC (g)	0.9	0.9		0.75
CH_4 (g)	0.02	0.02		0.02
SO_2 (g/)	0.01	0.01		0.009
N_2O (g)	0.01	0.01		0.01

a. Distance: 80 km (Jönsson 1995)

b. Round wood (softwood :pine): Density 775 kg/m^3
Moisture content: 70% (Jönsson 1995)

Raw material transportation [a]

Activity: Transportation (sawmill to pellet mill)	Data as collected	Normalized per activity	Linked flows, normalized to F.U.	Flows passing system boundary, normalized to F.U.
Inflows				
Sawdust [b] (m^3)	585000	1	0.3757	
Bark [c] (m^3)	90000	0.2	0.0578	
Energy (MJ)	7389979.2	12.6		4.7460
Outflows				
sawdust (m^3)	585000	1	0.3757	
Bark (m^3)	90000	0.2	0.0578	
CO_2 (g)	546516000	934.2		351
CO (g)	752094	1.3		0.5
NO_x (g)	3654720	6.2		2.3
PM (g)	61335	0.1		0.04
HC (g)	240264	0.4		0.15
CH_4 (g)	5752.8	0.01		0.004
SO_2 (g)	2757.96	0.005		0.002
N_2O (g)	3933.9	0.007		0.003

a. Distance: 100 km *(Neova)*

b. Sawdust: Bulk density 240 kg/m^3
Moisture content: 50% (Loo and Koppejan 2008)

c. Bark: Bulk density 320 kg/m^3
Moisture content: 50% (Loo and Koppejan 2008)

Appendix Ⅲ. Electricity Production

Electricity production based on different energy sources during 2006 (IEA 2006)

Sweden	Quantity (GWh) - Percentage %							
	Coal	Oil	Natural gas	Nuclear	Hydro	Wind	Biomass	Waste
Quantity	1991	1669	582	66977	61738	987	7791	1564
Percentage	1.39	1.16	0.41	46.74	43.08	0.69	5.44	1.09

The following table is inventory table for electricity production. The data relate to a functional unit of 1kWh electricity delivered from the power plant.

Electricity Production according to electricity production mixed of Nuclear, Hydropower, Wind-power, Gas, Oil and Biomass.

Resources depletion		
Bauxite	6.64E-05	g
Bio fuel	1.28E-06	kWh
Coal	2.14E-03	kWh
Copper ore	1.03E+00	g
Iron ore	3.34E-02	g
Lead ore	1.19E-02	g
Natural gas	5.81E-04	kWh
Uranium ore	6.03E-01	g
Heavy oil	1.87E-02	kWh
Emissions		
CO	8.13E-01	g
CO_2	2.76E+01	g
HC	3.76E-03	g
NO_x	3.58E-03	g
N-tot	1.24E-03	g
Particles	6.12E-03	g
SO_2	1.23E-02	g
Waste		
Building waste	3.34E-02	g
Highly active radioactive waste	2.20E-02	g
Low active radioactive waste	1.33E+01	ug
Other rest products	4.94E+01	g

Reference: CPM-LCI data base, (Brännström-Norberg, Dethlefsen et al. 1996)

The following tables are inventory table for electricity production systems based on different fossil fuel, nuclear and renewable resources. The data relate to a functional unit of 1kWh electricity delivered from the power plant.

Nuclear

Resources depletion		
Bauxite	8.67E-02	mg
Bio fuel	2.00E-06	kWh
Coal	4.28E-03	kWh
Copper ore	2.07E+00	g
Iron ore	3.46E-02	g
Lead ore	6.63E-03	g
Natural gas	9.22E-04	kWh
Uranium ore	1.24E+00	g
Heavy oil	3.52E-03	kWh
Emissions		
CO	3.72E-03	g
CO_2	2.55E+00	g
HC	1.02E-03	g
NO_x	1.58E-02	g
N-tot	3.27E-04	g
Particles	7.64E-03	g
SO_2	1.34E-02	g
Wastes		
Building waste	6.78E-02	g
Highly active radioactive waste	4.53E-02	g
Low active radioactive waste	2.74E+01	ug
Other rest products	1.96E+01	g

Reference: (Brännström-Norberg, Dethlefsen et al. 1996)

Hydro-power

Resources depletion		
Bio fuel	4.98E-07	kWh
Coal	1.01E-04	kWh
Copper ore	6.21E+01	g
Iron ore	2.94E+01	g
Lead ore	1.97E+01	g
Natural gas	3.00E-06	kWh
Heavy oil	7.00E-05	kWh
Emissions		
CO	1.80E+00	g
CO_2	6.77E+01	g
HC	2.47E-01	g
NO_x	2.63E-01	g
N-tot	3.21E-01	g
Particles	2.95E+01	g
SO_2	1.09E-01	g
Wastes		
Other rest products	8.94E+01	g

Reference: (Brännström-Norberg, Dethlefsen et al. 1996)

Wind

Resources depletion		
Bio fuel	1.00E-06	kWh
Coal	1.46E-03	kWh
Copper ore	5.90E-01	g
Iron ore	4.12E-02	g
Natural gas	5.00E-06	kWh
Heavy oil	3.20E-05	kWh
Emissions		
CO	3.25E+01	g
CO_2	6.07E-02	g
HC	1.64E+01	g
NO_x	1.39E-01	g
N-tot	4.32E-01	g
Particles	3.30E+01	g
SO_2	1.52E-01	g
Wastes		
Building waste	3.67E-01	g
Other rest products	1.31E-02	g

Reference: (Brännström-Norberg, Dethlefsen et al. 1996)

Gas

Resources depletion		
Bio fuel	2.29E-07	kWh
Coal	3.19E-04	kWh
Iron ore	9.07E-02	g
Natural gas	3.53E-02	kWh
Heavy oil	3.89E+00	kWh
Emissions		
CO	1.12E+00	g
CO_2	1.04E+03	g
HC	6.14E-01	g
NO_x	3.49E+00	g
N-tot	1.00E-06	g
Particles	6.65E-02	g
SO_2	8.53E-01	g
Wastes		
Other rest products	2.67E-01	g

Reference: (Brännström-Norberg, Dethlefsen et al. 1996)

Oil

Resources depletion		
Bauxite	6.07E-03	g
Bio fuel	4.00E-06	kWh
Coal	2.94E-04	kWh
Copper ore	6.97E-04	g
Iron ore	6.39E-02	g
Natural gas	2.33E-02	kWh
Heavy oil	9.54E-02	kWh
Emissions		
CO	1.60E-01	g
CO_2	7.14E+02	g
HC	4.05E-01	g
NO_x	6.46E-01	g
N-tot	1.37E-04	g
Particles	1.04E-01	g
SO_2	5.40E-01	g
Wastes		
Building waste	1.86E-02	g
Other rest products	1.03E-01	g

Reference: (Brännström-Norberg, Dethlefsen et al. 1996)

Biomass

Resources depletion		
Fuel wood	3.98E+02	g
Bio fuel	1.00E-06	kWh
Coal	1.71E-04	kWh
Copper ore	1.60E-02	g
Iron ore	4.80E-02	g
Natural gas	4.80E-05	kWh
Heavy oil	3.54E-02	kWh
Emissions		
CO	2.13E-01	g
CO_2	3.40E+02	g
HC	1.40E-02	g
NO_x	3.33E-01	g
N-tot	1.64E-02	g
Particles	2.90E-02	g
SO_2	4.17E-02	g
Electricity	1.00E+00	kWh
Wastes		
Other rest products	5.47E+00	g

Reference: (Brännström-Norberg, Dethlefsen et al. 1996)

Appendix Ⅳ. Weighting factors

Ecoindicator 99

Substance	Damage category	Hierarchist weights	Egalitarian weights	Individualist weights
Emissions to air (/kg)				
CO	Human health, respiratory	0	0.0141	0
CO_2	Human health, climate	0.00545	0.00406	0.0133
NO_x NO_2	Human health, respiratory	2.3	1.72	0.0793
	Ecosystem quality, acidification and eutrophication	0.445	0.557	0.317
	Sum, NO_x to air	2.745	2.277	0.3963
SO_2	Human health, respiratory	1.42	1.06	0.717
	Ecosystem quality, acidification and eutrophication	0.0812	0.101	0.0577
	Sum, SO_2 to air	1.5012	1.161	0.7747
CH_4	Human health, climate change	0.114	0.0852	0.293
	Ecosystem quality, acidification and eutrophication	0.0467	0.0348	0.0809
	Sum, CH_4 to air	0.1607	0.12	0.3739
N2O (nitrous oxide)	Human health, climate	1.79	1.34	4.47
Particulates, PM_{10}	Human health, respiratory	9.74	7.26	18.3
Resources use (kg)				
Copper	Damage to Resources caused by extraction of minerals	0.00987	0.014	0.533
Iron	Damage to Resources caused by extraction of minerals	0.00069	0.000976	0.0387
Lead	Damage to Resources caused by extraction of minerals	0.00875	0.0124	0.491
Bauxite	Damage to Resources caused by extraction of minerals	0.0119	0.0168	0.667
Hard coal	Damage to Resources caused by extraction of fossil fuels	0.00599	0.0687	0
Oil	Damage to Resources caused by extraction of fossil fuels	0.14	0.114	0
Natural gas	Damage to Resources caused by extraction of fossil fuels	0.108	0.0909	0

EPS2000

Substance flow group	Impact index,(ELU/kg)
Emission to air	
CO_2	0.108
CO	0.331
NO_x	2.13
PM_{10}	36.0
SO_2	3.27
CH_4	2.72
N_2O	38.3
Sum	
Resources use	
Copper	208
Iron	1.23
lead	240
Bauxite	0.443
Uranium	1190
Coal	0.0498
Oil	0.506
Natural gas	1.1
Wood (kg)	0.04

EDIP

Parameter	EDIP
Emission to air	
CO2	0.000000149
CO	0.00000236
NOx	0.0000154
PM	
HC	0.0000364
SO2	0.0000109
CH4	0.00000416
N2O	0.0000484
Resource use	
Fossil oil	0.000039
copper	0.016
Iron	0.000085
lead	0.075
Bauxite	0.0015
Uranium	
Coal	0.00001
Oil	0.000039
Natural gas	0.000052