Wood pellets and Salix district heating

- A comparative LCA of two forms of biofuel heating

Project of Group 03 in course AG2800 Life Cycle Assessment

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2015-01-14 The Royal Institute of Technology

Abstract

Biofuel is an increasing energy source in Sweden that can be used for household heating instead of for example fossil fuels. In this report two different types of biofuel heating systems for heating up a small family house located in Sweden are compared in an accounting life cycle assessment (LCA). The two alternatives considered are heating from wood pellets made out of sawdust and district heating from incineration of Salix plant. The purpose of this study is to investigate which type of heating system contributes to the most environmental impacts and also, where in the life-cycle that the largest impacts occur.

A cradle-to-grave approach was applied and the software SimaPro 7 used in order to evaluate 18 different impact categories. Several assumptions were made concerning the system boundaries, material and allocation problems. Both generic and primary data was used in order to model the life cycle of each of the systems.

The results from the study found that the life cycle of the district heating from Salix was more favourable than that of the heating from wood pellets life cycle in terms of total environmental impact. The impacts were for both alternatives mainly caused by the incineration process due to emissions. Fertilizers in cultivation of Salix and the land occupation for cultivation of both tree and Salix also contribute to a larger extent to the environmental impacts.

The recommendation for a household in Sweden that consider to use biofuel for heating in order to decrease the environmental impacts as much as possible is to choose district heating from Salix over combustion of wood pellets. The LCA does not however include aspects such as economy, user perspective or ability to use technology.

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1 Goal and scope

1.1 Goal of the study

The awareness of climate change and other environmental impacts has increased over the years. One of the sources to an increased emission of carbon dioxide and global warming is the burning of fossil fuels when used for heating, electricity, transport etc. It is desirable to reduce these emissions with the same amount of energy delivered. A current option to fossil fuels to heat houses is the renewable energy source biofuels. In Sweden the use of biofuels has increased in recent years in different sectors.

There are different types of biofuels which can be used in different forms for household heating. Two of the most common ones used in Sweden are pellets and energy crops (Svebio, n.d.). Pellets can for example be made out of wood, which is an economical energy source based on raw material that can be acquired from within the country (SCA, 2014c). One type of energy crop also grown in Sweden is Salix. This is a fast growing and perennial plant species that includes Willows (Jordbruksverket, n.d.).

Two energy systems based on biofuels, currently in use in Sweden, are district heating and combustion in a furnace located within the household. Pellets are usually the form of biofuel that is used for incineration within the house, while energy crops are suitable to use in big furnaces like the ones used in district heating systems (Energimyndigheten, 2014). These two examples are differing in scale, both for cultivation, production of heat and the number of households that can be supplied at the same time. District heating can supply thousands of households from one power plant. Wood pellets are produced in a factory and usually distributed to different households, where they are combusted in a furnace located within the house. Even though the scale varies for the two systems, a comparison between these is found to be relevant since the systems are common options for household heat in small family houses in Sweden today (Energimyndigheten, 2011).

Due to the lower emissions of carbon dioxide and the need to decrease the usage of fossil fuels it is interesting to study the environmental impacts of biofuel alternatives for household heating. In Sweden the household heating is important due to a cold climate the majority of the year. Due to the different alternatives of biofuels used for household heating, it is interesting to compare the environmental impacts of different biofuels to each other. This includes the whole system, from cradle-to-grave. In this study two types of systems for heating using biofuels will be investigated, the before mentioned district heating from Salix and heat from wood pellets.

The main aim of the study is to see which of the heating systems contribute to the most environmental impacts and also, where in the life-cycle that the largest impacts occur. A comparative life cycle assessment (LCA) will be performed using the software SimaPro 7 in order to investigate the environmental impacts of the two heating systems. The LCA will have a cradle-to-grave approach, where wood pellets and district heating with Salix are used for heating up a small family house in Sweden for one year. The study will be a so-called accounting LCA, since it is analysing two current and available energy systems as they are today. A sensitivity analysis will be performed in order to test the robustness of the results.

The LCA can be a guide for families in order to decide on which system to use for heating their household. Manufacturers could also use the result in order to see if the product they provide can be improved and in that case in which step of the life-cycle this can be done.

1.2 Functional unit

The functional unit is the basis of the life cycle analysis, allowing different options and processes to be compared and analysed. The functional unit is set to 20 000 kWh of heat available to a small family house for one year. This value is based on data from the Swedish Energy Agency stating that the average Swedish small family house uses 4500 kWh every year for heating up hot water and 13 500 kWh for heating up the house (Energimyndigheten, 2012). This functional unit of 20 000 kWh is to be kept as a reference for all calculations made in the comparative life cycle assessment.

1.3 System boundaries

An accounting LCA typically considers the complete life cycle of a product, from the “cradle” to the “grave”. This includes many processes, inputs and outputs that need to be modelled in the analysis. It is thus important to decide on which system boundaries to use, especially since the comparison needs to be as fair and transparent as possible. The system boundaries needs to be defined in both a geographical and temporal dimension, as well as pointing out cut-offs and allocation problems in the processes. (Baumann and Tillman, 2005)

For both scenarios studied in this LCA, personnel-related environmental impacts are not included. Where production of capital goods is included it is allocated and environmental impacts of the maintenance of capital goods are not included in the analysis. Both scenarios are taking place in Sweden and it is assumed that European data can be applied for this Swedish case.

1.3.1 System boundaries of the wood pellets scenario

System boundaries have been identified for the wood pellet system through a chosen scenario illustrated in a flowchart in Figure 1. In this scenario the cradle of wood pellets is the forest, which starts in the plantation. The end of the LCA is the ash waste disposal which occurs after the incineration process. As illustrated in the flowchart the first process (the planting of the trees) and the usage of the heating in the LCA is not included within the system boundary. The cultivation of the trees is considered due to the fact that fertilizer is used, which is considered to have an impact on the study outcome.

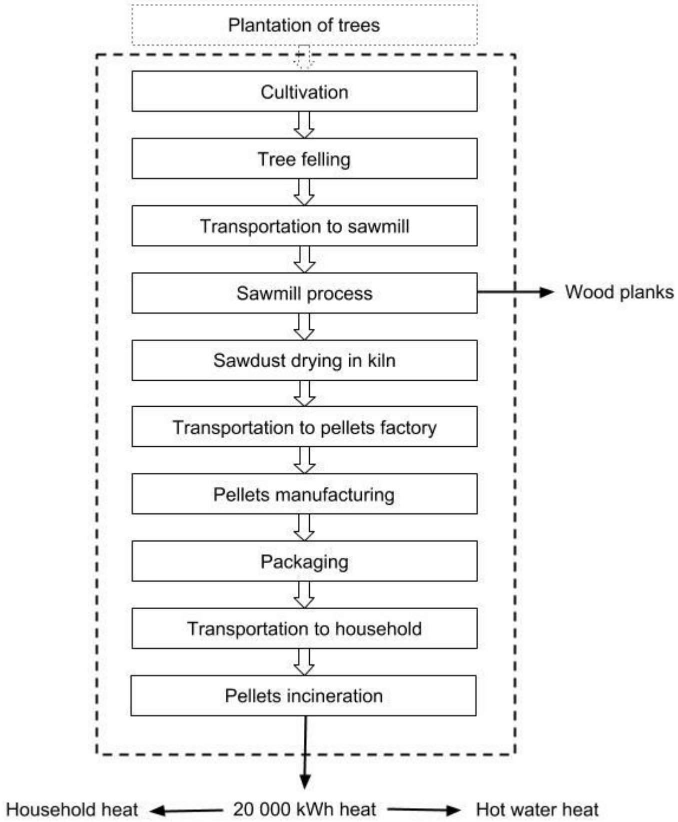

Figure 1 Initial flow chart of the scenario of a household using wood pellets as heat source.

The wood chosen is Scandinavian softwood, more precisely fir trees (norrländsk furu). The trees in the scenario are grown in the north of Sweden in SCA (Swedish Cellulose Limited Company) owned forests in approximation to Bollsta sawmill. Sawdust from the sawmill is then transported by lorry to a pellet factory in Härnösand, also owned by SCA. After the production of the pellets they are distributed to a household in Mälardalen, incinerating the pellets for household heat and hot water.

1.3.2 System boundaries of the Salix district heating scenario

The system boundaries for district heating using Salix as a fuel have been identified and can be seen in Figure 2. The steps included in the system are from the cultivation of Salix plants to the arrival of the produced district heating to the family house. Salix is, after cultivation, harvesting and chipping, transported to a district heating plant where it is incinerated in a furnace. From this, water is warmed up and works as a transporter of heat to the households in the district. Each house receiving district heat has a heat exchanger inside the house.

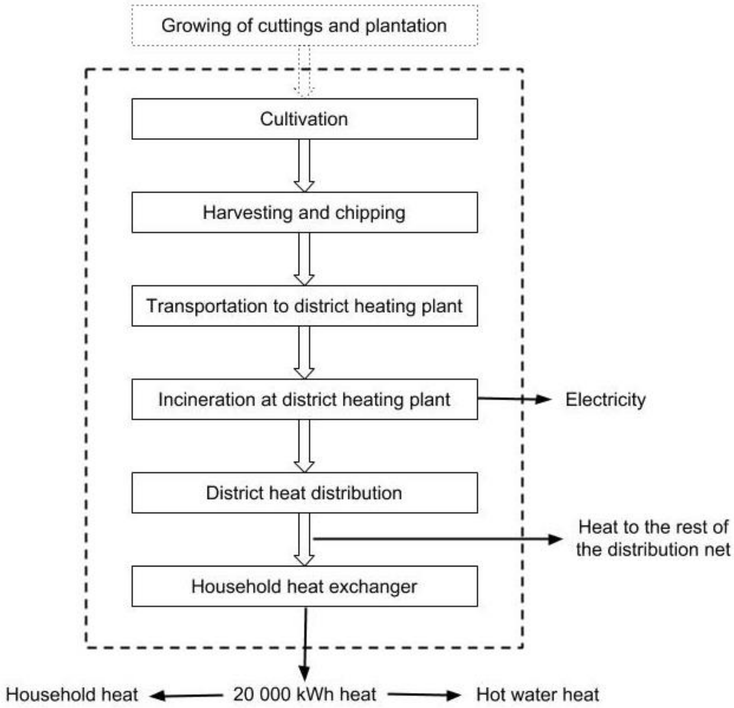

Figure 2 Initial flow chart of the scenario of a household using district heat from Salix.

Mälardalen is chosen as the location where the Salix is cultivated, processed and used for district heating. This particular area is considered, because the majority of the Salix cultivation in Sweden is done here (Jordbruksverket, 2014). The LCA will consider the environmental impacts of Salix district heating from the cultivation to the distribution of the heat to the house.

The Salix is usually planted in the field in the form of cuttings. After the Salix has been cultivated for approximately three years, it is set to be harvested and at the same time chipped. The chipped Salix is then transported by lorry to a biofuel district heating plant located in Enköping. The waste of this scenario is ashes from the incineration at the plant.

1.3.3 Cut-off Criteria

The system boundaries are drawn so that for the heating from wood pellets scenario does not include the planting of the trees (the first process in figure 1) and the usage of the heating in the household. The cultivation of the trees is, on the other hand, considered due to the fact that fertilizer is used, which is considered to have an impact on the study outcome.

The cultivation of the Salix cuttings prior to field plantation will not be considered in the study and is placed outside the system boundary, as seen in figure 2. The preparatory and restoration work of the field will not be considered either. The reason for these cut-offs is that the environmental impacts of these sub-processes are judged to be negligible since the same Salix plant can be cultivated multiple times. The environmental impacts from manufacturing the leased harvesting machine are also cut off. However, the cultivation of Salix in the field is considered due to the fact that fertilizers are used, which is considered to have a relevant impact in the study.

1.3.4 Allocation problems

There is a multi-output allocation problem in the heating from wood pellet scenario. It occurs in the sawmill, since wooden planks are produced besides the sawdust used in the wood pellets. The environmental loads of the processes up to this point in the life cycle are partitioned with an allocation factor based on the mass relationship between the planks and the sawdust from one trunk.

A multi-output allocation problem occurs in the district heating plant, since the incineration of Salix results in both heat and electricity. In this study, only the environmental loads corresponding to the heat is to be assessed. This is resolved by partitioning the environmental loads of the life cycle up to this point with an allocation factor corresponding to the ratio between produced MJ heat and electricity.

Furthermore, there is an allocation problem with the district heating plant distributing heat to more than just the one household assessed here. Instead, the used district heating plant delivers heat to approximately 2000 households. The impacts of the district heating plant itself, the distribution system and the produced heat will be divided evenly among the households in order to only include the environmental loads corresponding to one household.

1.3.5 Time Horizon

This accounting LCA investigates the current situation of two different biofuel heating systems. If any large changes occur for the two alternatives the results from a comparison could possibly change. It is however not a type of system where very large and rapid developments usually take place (for example in contrast to the IT industry). It can therefore be assumed that the result from this comparative and accounting LCA is applicable for some years ahead.

Both present and past data will be used and is based on the Ecoinvent Database v2.2 and LCA Food DK, as implemented in SimaPro 7. Data is taken from the mid 1990's to present time. The validity of the model depends on if the technology is still the same or similar in the future. When transportations and processes in the heating systems are made more effective or changed, the validity of the model will decrease.

1.4 Assumptions and limitations

A life cycle assessment consists of a number of assumptions and limitations affecting the outcome of the assessment. These are outlined here in order to make the assessment as transparent as possible. In both scenarios, Ecoinvent v2.2 and LCA Food DK data in SimaPro 7 is assumed to be valid for these Swedish conditions. Average data is used since the LCA is attributional. All transports are assumed to be diesel driven and the electricity is as far as possible based on Swedish average data (also found in Ecoinvent v2.2 in SimaPro 7).

1.4.1 Assumptions and limitations of the wood pellets scenario

- The pellets used by the household in the study correspond to Bionorrpellets produced by SCA Bionorr (SCA, 2014d).
- Typical commercial fertilizers are used for the cultivation process (SCA, 2014b).
- The type of tree used for the wood pellets is Scandinavian Softwood (fir trees) (SCA, 2014a).
- The trees are cultivated during a 75 year period.

- Sawdust from these trees is used solely for the pellets.
- The relationship between the produced wooden planks and the sawdust is assumed to be 60/40 (Orvén, 2014).
- The transportations between the forest, the sawmill and the pellet factory are done by diesel driven lorries. The lorries return empty.
- The transportation between the pellet factory and the household is done by small, diesel driven lorries.
- The pellets are delivered directly from the pellet production facility to the household.
- The efficiency of the incineration furnace in the household is 82% as the Ecoinvent v2.2 data stated in SimaPro 7 (Heat, wood pellets, at furnace 15kW/SE U).

1.4.2 Assumptions and limitations of the Salix district heating scenario

- Typical commercial fertilizers are used for the cultivation process (Börjesson, 2006).
- The Salix is assumed to be cultivated during three years, with the same amount of fertilizing every year, before harvesting (Börjesson, 2006).
- The harvesting machine is driven by diesel fuel and chips the Salix directly.
- The transportation between the Salix field and the district heating plant is with diesel driven lorries. The return ways of the lorries are empty.
- All heat is assumed to be produced by burning Salix grown in Mälardalen only, in reality there might be a mix of biofuels from different plantations.
- The district heating plant is assumed to distribute heat to 2000 households, all requiring the same amount of heat.
- The environmental loads of the district heat distribution system are partitioned evenly between the households, although there are different distances between all houses and the power plant.
- The efficiency of the district heating plant is 90% (Svensk Fjärrvärme 1, n.d.).
- The energy loss in the distribution system is 10% (Svensk Fjärrvärme 2, n.d.).
- No heat losses occur in the household's heat exchanger
- The lifetime of the district heat infrastructure and the plant is assumed to be 30 years (Olivier-Sola, Gabarell and Rieradevall, 2009).
- The lifetime of the household heat exchanger is assumed to be 20 years (MälarEnergi, n.d.).
- The combustion of Salix is modelled to be incineration of Softwood chips found in Ecoinvent v2.2.
- The relationship between produced electricity and heat is assumed to be 30/70 (Ena Energi, n.d.).

1.5 Impact categories and impact assessment method

In order to be able to interpret the calculated inventory result a life cycle impact assessment (LCIA) method will be used. The chosen method is the ReCiPe method. The ReCiPe method divides the Life Cycle Inventory Result into indicator scores. These indicator scores state the relative severity of the impact categories (Goedkoop et al, 2008). For this LCA study, midpoint methodology and a hierarchist (egalitarian) perspective will be used. The method includes the following environmental impact categories:

- Climate Change
- Human toxicity
- Particulate matter formation
- Terrestrial acidification
- Marine eutrophication

- Ozone depletion
- Photochemical oxidant formation
- Ionizing radiation
- Freshwater eutrophication
- Terrestrial ecotoxicity

- Freshwater ecotoxicity
- Agricultural land occupation
- Natural land transformation
- Metal depletion

- Marine ecotoxicity
- Urban land occupation
- Water depletion
- Fossil depletion

In this study all environmental impact categories will be considered. The reason for this is should a category be excluded there is a risk of it not being discovered. It is desirable that no impacts are missed from the start and therefore, all impact categories have been chosen.

1.6 Normalisation and weighting

A normalisation procedure is used to show to what degree an environmental impact category has in relation to the overall environmental impact. In other words, it shows which categories have the most significant effects. By selecting a normal value and dividing the category indicators by this value, it is easier to evaluate which impact category contributes to the general environmental problem of the system. The normalisation method that is used in this study is the European ReCiPe H, this due to that the study is located in Europe. H stands for the above mentioned hierarchist, which means that an egalitarian perspective is used. The impacts will not be weighted as this is not allowed for comparative assertions according to the ISO standard for LCA (Finnveden, 2014). Furthermore, weighting is not included in the midpoint methodology.

2 Life cycle inventory analysis

2.1 Detailed process flowcharts

The detailed process flowcharts for the two scenarios compared can be seen in Figure 3 and Figure 4. The system boundaries are marked with dashed lines. All processes within the system boundary belong to the foreground system, which is the system of primary concern. All flows and processes outside the system boundary represent the background system which delivers materials and energy to the foreground system but also represent the outcome and rest products. The outputs marked in red in the flow charts represent allocation problems.

The flowchart in Figure 3 shows the interlinked processes and product flows for the wood pellets scenario. The allocation problem in this process is the manufacturing of wood planks, from which the sawdust for the wood pellets is acquired. The flowchart in Figure 4 shows the interlinked processes in the scenario of using district heating from Salix. Here it can be seen that there are two identified allocation problems; produced electricity from the incineration process at CHP-plant and heat distribution to the rest of the district heat network.

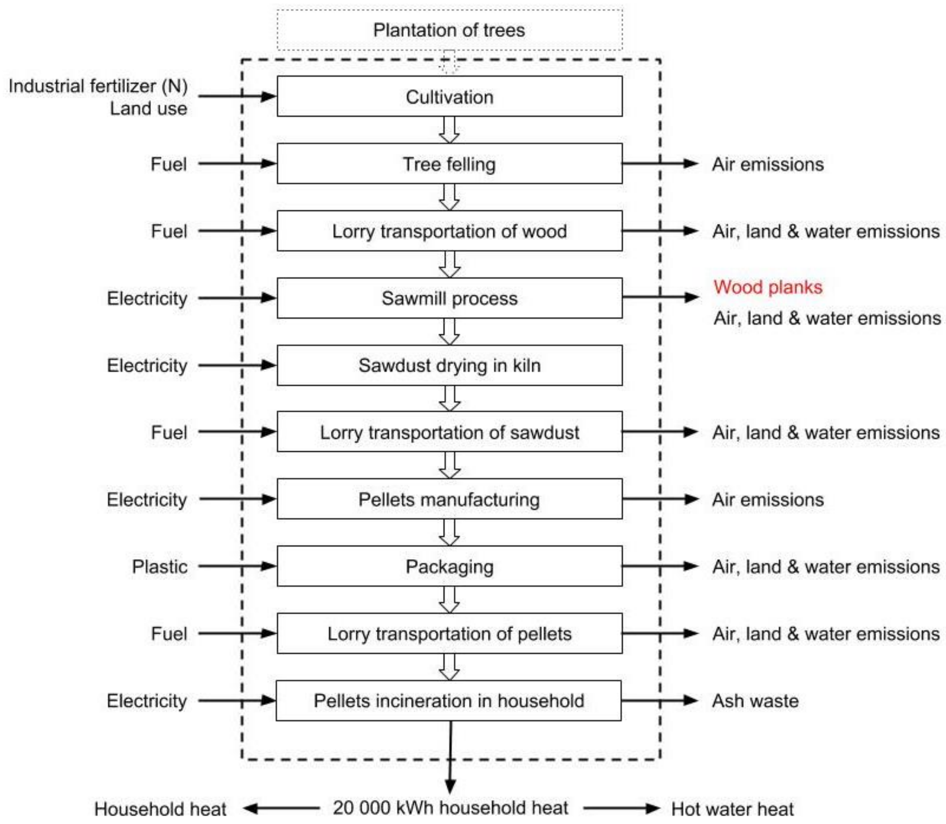

Figure 3 Detailed flow chart of the scenario using wood pellets incineration within the household. The processes that are cut off are marked with dashed lined boxes. The output resulting in an allocation problem is marked in red.

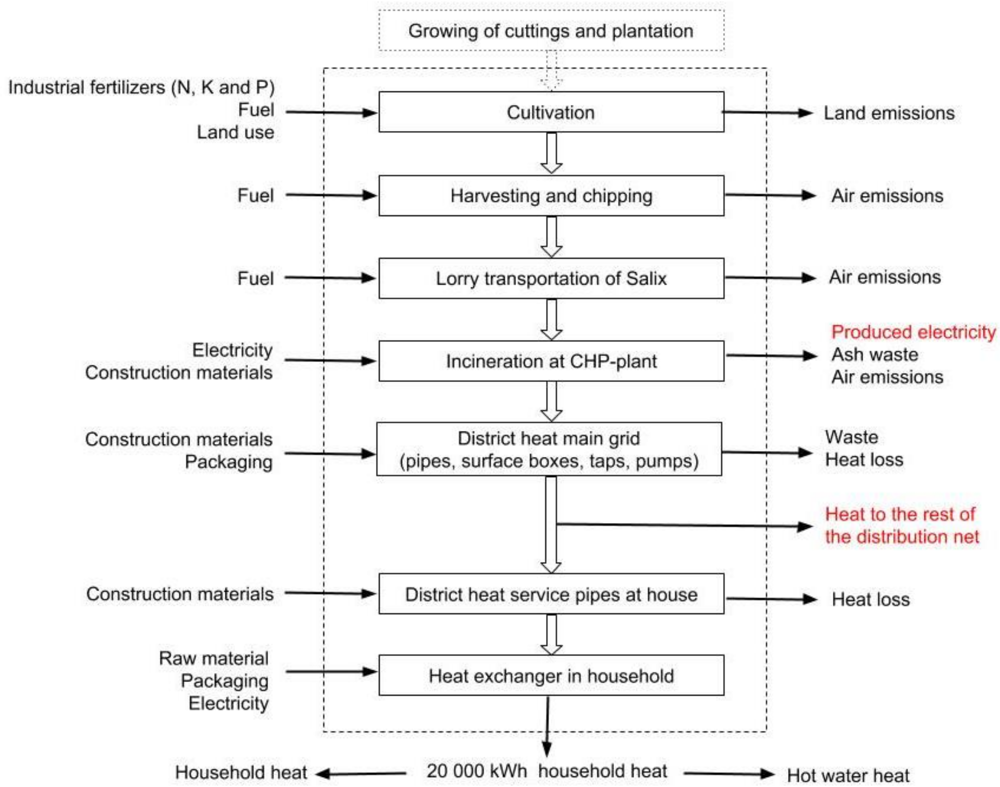

Figure 4 Detailed flow chart of the scenario using district heat from Salix. The processes that are cut off are marked with dashed lined boxes. The outputs resulting in allocation problems are marked in red.

2.2 Data Inventory

2.2.1 Data on the wood pellets scenario

In order to deliver 20 000 kWh (72 GJ) heat per year to a household 4.9 tonnes of pellets are needed. The pellet type Bionorrpellets from the company SCA are used in the study, which are manufactured out of sawdust. For production of 4.9 tonnes pellets approximately 9.8 tonnes of sawdust with a moisture content of 50 percent is needed (Orvér, 2014). According to Agrol (2014) about 60 percent of the amount of forest wood is used to produce the sawmill's main product, wooden planks. The remaining 40 percent are rest products in the form of sawdust. It is assumed that all of the sawdust in this scenario is used for production of Bionorrpellets. The ratio between wooden planks and sawdust is assumed to be valid as partitioning of this allocation problem. Therefore, to obtain 9.8 tonnes of sawdust this in turn corresponds to a volume of 30.6 m^3 sawdust. To produce 30.6 m^3 a total volume of 22.8 m^3 wood is needed. The fertiliser used to produce this wood is 9.5 kg of nitrogen (SCA, 2014). All calculations are found in Appendix 1.

The pellets are manufactured at the pellet factory, packaged into plastic bags (made out of polyethylene) and later on transported directly to the household on pallets of 832 kg (Neova, n.d.). One pallet consists of 52 plastic bags of 16 kg of wood pellets each. The process of packaging lime products is assumed to be applicable for the packaging of the wood pellets. It is assumed that the household will receive two pallets delivered on average 3 times a year.

The distance between the sawmill and the pellets factory is estimated to 50 km. The sawdust is transported to the factory by diesel driven lorries. It is assumed that the lorries drive full to the factory and back empty. The distance between the pellet factory and the household in Mälardalen is 400 km. The pellets are distributed to the household with small diesel driven lorries. The pellets are finally incinerated in a furnace located in the household. The furnace has an efficiency of 82 %. The ash waste from the incineration is disposed as municipal incineration and landfarming, according to the used incineration process from Ecoinvent v2.2 as implemented in SimaPro 7.

Presented in Appendix 2 are the result from the data inventory and the used input processes in SimaPro 7 for the different system processes from cultivation to incineration.

2.2.2 Data on the Salix district heating scenario

On average, the life length of a Salix plantation is 22 years where harvesting takes place every third year. The harvesting machine chips the Salix directly and is driven by diesel fuel with a heating value of 45 MJ/kg. The amount of required fertilizers differs somewhat during the life length of one plantation, but average values used per hectare and cultivation year can be seen in Appendix 3. (Börjesson, 2006.)

A lower heating value of 16.5 GJ per tonnes dry matter harvested Salix is being used. Taking into account the somewhat lower yields in the beginning of the plantation life time, each hectare of Salix plantation yields 155 GJ every year, weighing approximately 10 tonnes. The emissions from and the energy required by the harvesting process can also be seen in Appendix 3. (Börjesson, 2006.)

The transportation from the plantation to the district heating plant is assumed to be by a diesel driven lorry for 30 km, carrying 10 tonnes of Salix each time. The return rides to the plantation are assumed to be empty. The data for this transportation is collected from the Ecoinvent v2.2 Database in SimaPro 7.

A reference district heating plant located in Mälardalen is used to collect data and construct a model in SimaPro 7. The plant "Ena Energi" is located in Enköping and consists of different power and heating systems including a district heating plant using biofuels to deliver electricity and heat to approximately 2000 households in the surrounding area (Ena Energi, n.d.). The distribution between produced heat and electricity at "Ena Energi" is 24 MW electricity per 55 MW heat. The used partitioning ratio in the allocation procedure for the multi-output problem is therefore 30/70.

Energy losses will occur during production and distribution. According to the Swedish trade association for district heating the efficiency of a district heating plant is 90% (Svensk Fjärrvärme 1, n.d.). The energy losses that occur in pipelines of the distribution system of the district heat to the household is set to be 10% (Svensk Fjärrvärme 2, n.d). No losses occur in the heat exchanger.

The capital goods at the district heating plant included in the LCA is the furnace. The furnace is a CHP furnace with allocation as described above. The heat is then distributed to the users through a distribution network. This network consists of a main grid consisting of different components. These are district heating pipes, surface boxes, taps and pumps. The main grid is connected to service pipes in which the heat is distributed to the households where it finally reach the last step; the household's heat exchanger. The data for the distribution system is based on an existing LCA by Oliver-Sola, Gabarell and Rieradevall (2009) with some changes depending on available data in SimaPro 7. The ash waste from the incineration is disposed as municipal incineration, landfill and landfarming, according to the used incineration process from Ecoinvent v2.2 as implemented in SimaPro 7. The details of the different components and the data used for the distribution system is seen in Appendix 4.

The main grid's components are said to consist of different lengths and amounts. These numbers are also based on the LCA report by Oliver-Sola, Gabarell and Rieradevall (2009). In their report the main grid provides around 200 households with district heating, the values used for the main grid and the trench works in their study are therefore multiplied with 10. The values used for the case in this study are presented in Appendix 4. Note that the lifetime or allocation is not shown in these tables.

All calculations of different steps in the processes, from cultivation to usage, is found in Appendix 1. In Appendix 5 the result from the data inventory and the used input processes in SimaPro 7 for the different system processes from cultivation to incineration is presented.

3 Life cycle interpretation

3.1 Results

Under this section the result of the SimaPro 7 simulations are presented. The results are first presented separately for each scenario and then compared with each other. Finally, the results from the performed sensitivity analyses are described.

3.1.1 Results of the heating from wood pellets life cycle

Figure 5 shows the characterization result for the scenario using heat from wood pellets. The life cycle is here divided into three parts; pellet production, incineration and packaging of pellets. The pellet production includes cultivation, harvesting, sawmill operation, manufacturing of pellets and the transportation. The incineration process includes the combustion and the furnace. The environmental impacts for the majority of the impact categories, 12 out of 18, are from the incineration process. The pellet production has the greatest environmental impact for the six other impact categories. Packaging of pellets has only a small notable effect.

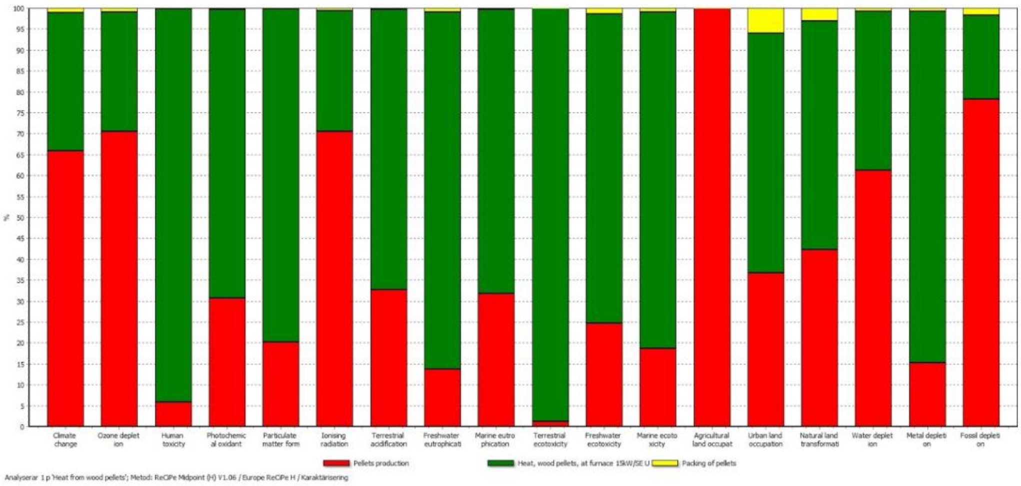

Figure 5 Characterised results of the environmental impacts from the heating from wood pellets life cycle.

Figure 6 shows the normalised result of the environmental impacts from the life cycle of heating from wood pellets. The agricultural land occupation has the greatest normalised score, which is caused by the pellet production assembly where the cultivation is included. The second greatest normalised score is human toxicity and it is mainly caused by the incineration process.

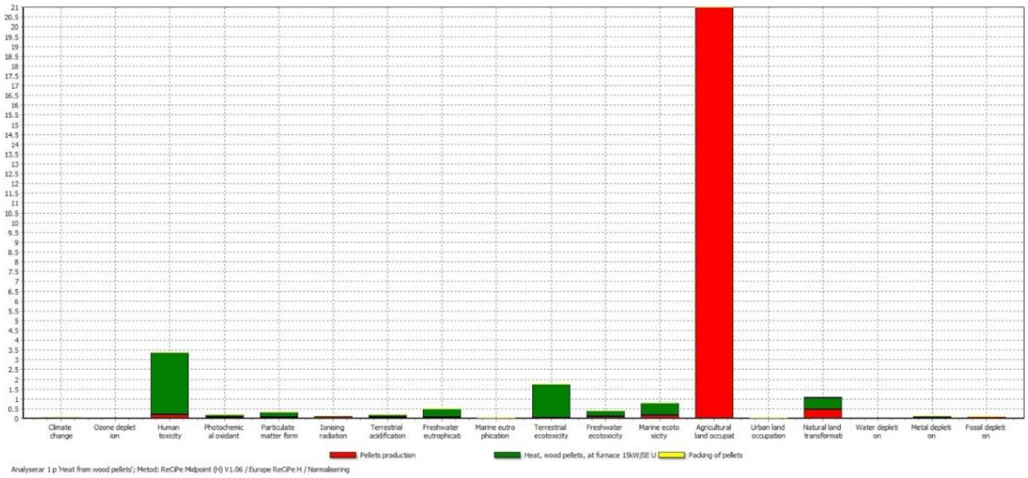

Figure 6 Normalised results of the environmental impacts from the heating from wood pellets life cycle.

3.1.2 Results of the district heating from Salix life cycle

Figure 7 shows the characterised results of the environmental impacts from the life cycle assessment of the district heat from Salix scenario. The life cycle is here divided into three parts; Salix acquisition process (cultivation, harvesting and transport), incineration and district heat infrastructure (including the district heat furnace). The Salix acquisition process has the greatest environmental impact on 8 out of 18 categories. The incineration process gives the greatest environmental burdens on the rest of the ten categories. The district heat distribution infrastructure is only showing a prominent impact in the metal depletion category.

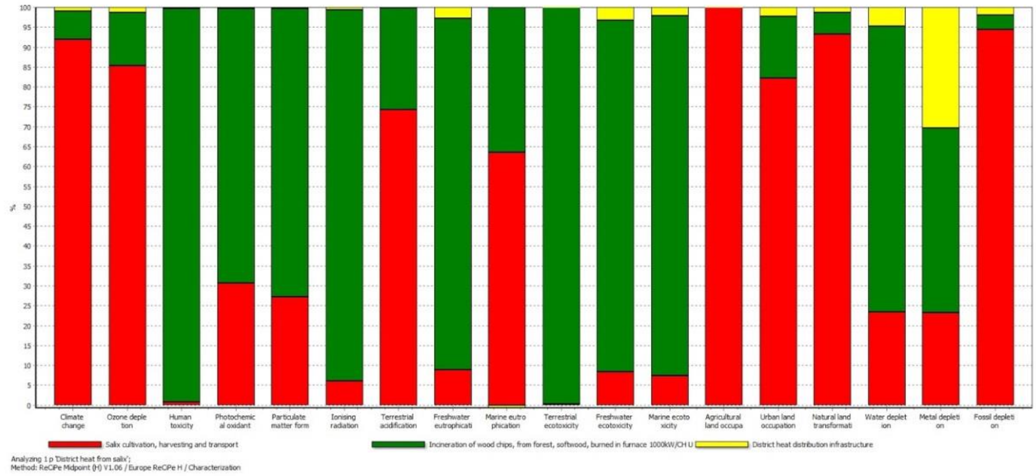

Figure 7 Characterised results of the environmental impacts from the district heating from Salix life cycle.

Figure 8 shows the normalised result of environmental impacts from the life cycle of district heating from Salix. The agricultural land occupation and human toxicity categories are greatest here. Agricultural land occupation is caused by the cultivation of Salix. The incineration process is the source of the impacts on human toxicity and terrestrial ecotoxicity due to emissions. The district heat infrastructure parts have a very low or no effects on the environmental impact categories when normalisation is performed.

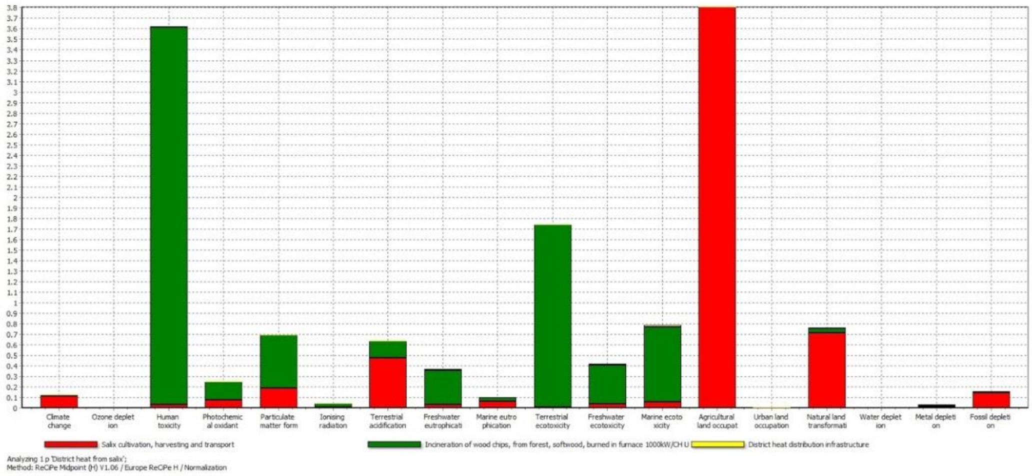

Figure 8. Normalised result of the environmental impacts from the district heating with Salix.

3.1.3 Comparison of the scenarios

Figure 9 shows the characterised environmental impacts from the life cycles of heating from wood pellets and district heating compared with each other. The comparison shows that heating from wood pellets give larger environmental loads in 9 out of 18 of the studied categories compared to district heat from Salix. In one category both scenarios give the same burdens. Fossil depletion and climate change are two of the categories where the Salix scenario gives larger impacts on, which is due to the higher usage of fertilisers.

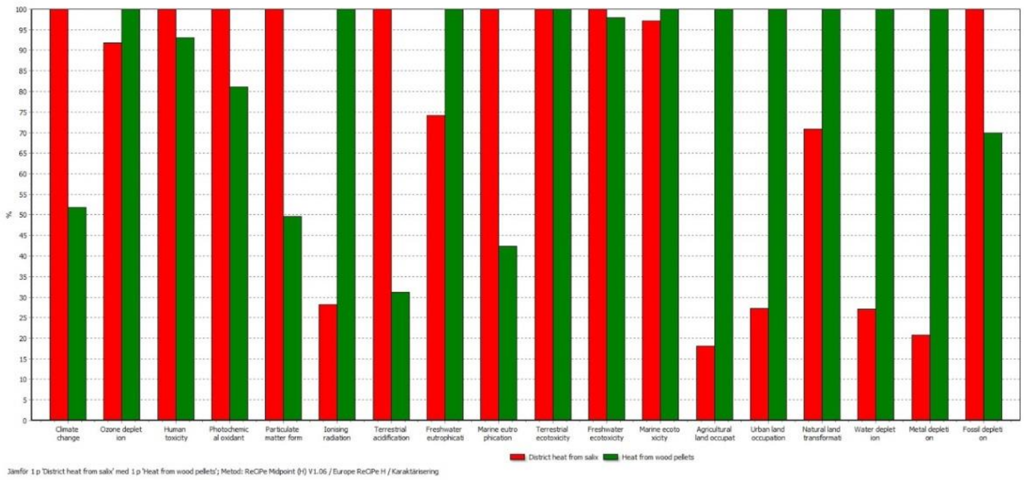

Figure 9 The characterised result of the environmental impacts from the district heating from Salix life cycle in red and and the heating from wood pellets life cycle in green.

Figure 10 shows the normalised environmental impacts from the life cycles of heating from wood pellets and district heating from Salix, in relation to the overall environmental impact in Europe. As seen in the figure, agricultural land occupation has the largest normalised score, followed by human toxicity. The reason for the higher agricultural land occupation level for the heating from wood pellet life cycle is due to that the Scandinavian Softwood has a longer cultivation period than Salix. The reason for the high human toxicity level from both scenarios is mainly due to the ash waste from the incineration processes in the two life cycles. The incineration process also affects the marine and terrestrial ecotoxicology.

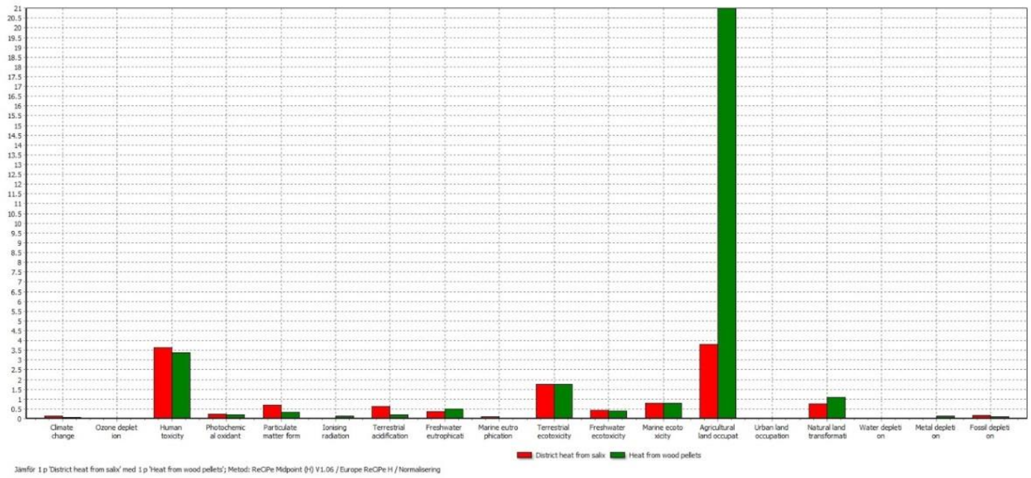

Figure 10 The normalised result of the environmental impacts from the district heating from Salix life cycle in red and the heating from wood pellets life cycle in green.

3.1.4 Sensitivity analysis

Sensitivity analyses were performed to test the robustness of the results. These were done by changing the value of certain parameters. Firstly, a distance was altered. In doing this, the model was checked to see if it was sensitive to location. Thereafter, the heat consumption was changed to a higher and a lower amount than originally. This was to see if the model was sensitive to the amount of heat a house would consume during a year. A house in the north of Sweden will likely consume more heat than a house in the south of Sweden.

The location of the household is assumed to be the same for both scenarios, located in Mälardalen. The distance from the district heating plant to the household is more than ten times as short as the distance between the pellet manufacturing and the household. It could thus be argued that this would be favourable for the Salix scenario, since the biofuel is transported a shorter distance and hence less diesel is consumed and in turn less emissions occur. In order to investigate how the location of the household affects the result of the study, a sensitivity analysis was performed where the distance from the pellets factory to the household was changed from 400 km to 10 km. The lifecycle for the district heat from Salix was kept the same as the original scenario. The results from the altered distance in the heating from wood pellets life cycle is seen in Appendix 6. The environmental impact for the impact categories is overall kept the same compared to the original scenario.

A sensitivity analysis was also performed where the heat demand for the house was changed according to two scenarios. The heat consumption was first changed to 40 000 kWh/year and then to 10 000 kWh/year for the two scenarios. This was done to see if the result would change for a house with a different heat demand. The resulting comparative characterisation graphs from this can be found in Appendix 6. The result from the sensitivity analyses showed that the environmental impact for the impact categories is overall kept the same compared to the original scenario.

3.2 Conclusions and recommendations

From the results it can be concluded that using district heat from incineration of Salix is a slightly better alternative compared to wood pellets for household heating in terms of total environmental impacts. This was also true for the cases where the transportation distances and the energy amounts were altered, implying that the result is valid for other locations and scales than the original case study.

However, an important observation from the result is that Salix contributes to a higher impact on climate change and fossil depletion. One would perhaps guess beforehand that the other scenario would give larger impacts in these categories, since it includes longer transports. The fact that it was fertilisers that gave the largest contribution to these categories led to this result. An important aspect of biofuels is that it is used mainly in order to decrease impacts of climate change by replacing fossil fuels. It could, therefore, be argued that Salix is not the better choice of the two, if the goal is to replace fossil fuels and generate the lowest impact on climate change and fossil depletion as possible.

Important factors that this LCA is not taking into account is the possibility to use the different heating systems in terms of availability, price and user perspective. In order to use district heating from Salix it must be possible to connect to a district heating distribution system. The household must be located in an area near a district heating plant and where a sufficient amount of households are located in order for the district heating plant to be economically feasible.

From a user perspective it could be argued that the district heating scenario is more desirable than the wood pellet scenario. More responsibility is put on the user in the latter scenario, since incineration of pellets within the household requires more effort than district heating. Heat from wood pellets is cheaper than district heating. The risk of being without heat due to power outage is also smaller for this scenario, since district heating distribution requires electricity. These aspects are all important to consider when deciding on what energy system to use, not included in this LCA. (Swedish Energy Agency, 2012)

Furthermore, it is also important to remember that there exists many energy alternatives not covered by this LCA. For example, the Swedish Energy Agency recommends wood pellet users to combine their heating system with solar heat (Swedish Energy Agency, 2012). The reason for this is the relatively low efficiency of the pellet furnace during the summer season when the heat demand is low. This is, however, not considered in this LCA. A different result outcome could have been acquired if this had been included in the study.

The results cannot only help the household to make a decision on what scenario to choose, but also give directions to manufacturers and heat suppliers on where to improve the product and decrease its environmental impacts. For both of the alternatives the incineration process has the largest impact in the life cycle due to emissions released during combustion. For district heating with Salix the fertilizers used during cultivation contribute to quite a large extent to the environmental impacts of the system. Using less fertilisers or a crop that requires less fertilisers would hence decrease the environmental impacts of this alternative further.

The availability of data for the two scenarios differed somewhat. Salix is a relatively new biofuel crop, not used in a large extent, and could therefore not be found in the already existing databases within SimaPro 7. Therefore, primary data based on scientific reports were used. This was also the case for modelling the district heating distribution system in this scenario. The study used as a base for modelling of the plant and the distribution system is located in Spain and for a plant providing 200 people with heat on a 100 m long street. If more time was given, it would have been desirable to have contacted the district heating plant in Enköping and obtained present data for the distribution system.

For the scenario using the wood pellets, generic data was to a high extent available and used from within the databases in SimaPro 7. The fact that it is generic data leads to different types of uncertainties, since they are not specifically chosen for this case and are typically including many processes and materials difficult to check. The control can be considered to be lower, but the complexity higher, for this type of data compared to the primary data from reports used.

Nonetheless, even though there are uncertainties, this comparative LCA is pointing towards using district heat from Salix if the household wants to choose the more environmentally friendly alternative, compared to using heat from wood pellets.

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Appendix 1

Calculations used for modelling of wood pellets heating scenario.
Amount of wood pellets needed to supply the demand of 20 000 kWh from a furnace with heat losses of 18% and with 4800 kWh delivered per tonne of pellets:

(20 000 [kWh] * 1.18) / 4800 [kWh/tonne] = 4.9 tonnes of pellets

The density of the wood is based on the dry-raw density which is 430 kg/m^3 (Svenskt Trä, n.d). This data is used to calculate the total volume of wood:
9800 [kg sawdust] / 430 [kg/m^3] = 22.8 m^3

The density of sawdust 320 kg/m^3s, this is needed to calculate total volume of sawdust:
9800 [kg sawdust] / 320 [kg/m^3] = 30.6 m^3

The density of pellets is assumed to be 670 kg/m^3 (Kole et al., 2012). Total volume of wood pellets:
4900 [kg pellets] / 670 [kg/m^3] = 7.3 m^3

The amount of fertiliser used
27.7 [m^2 land / m^3 Softwood] * 22.8 [m^3 Softwood] = 632 m^2 = 0,0632 ha
0.0632 [ha] * 150 [kg Nitrogen/ha] = 9.5 kg Nitrogen

Calculations used for modelling of Salix district heating scenario.
20 000 [kWh] * 2000 [households] = 40 000 000 kWh for the whole district heat network

10 % heat loss in distribution net and 10 % heat loss at combustion makes the required amount of dry matter of Salix to be worth 4 938 000 kWh to the district heat plant.

4 938 000 [kWh] * 3 600 000 = 178 *10^{14} J = 177 768 GJ

1 tonne of harvested Salix is worth 15.5 GJ → 11 470 tonnes harvested Salix is needed for the whole district.

Appendix 2

Processes used in SimaPro 7 for heating with wood pellets life cycle.

Table i Processes used for the wood pellets life cycle

System process	*Component*	*Input process in SimaPro 7*	*Amount in model*	*Unit*	*Database*
Cultivation of softwood	Fertilizers	Fertilizer (N)	9.5	kg	LCA Food DK
	Scandinavian softwood	Softwood, Scandinavian, standing, under bark, in forest/NORDEL S	22.8	m^3	Ecoinvent v2.2
	Machinery	Excavation, skid-steer loader/m3/RER[1]	22.8	m^3	Modified process
Sawmill operation	Sawdust	Sawdust, Scandinavian softwood (plant-debarked), u=70%, at plant/m3/NORDEL[2]	30.6	m^3	Modified process
	Transport of sawdust to pellet factory	Transport, lorry 16-32t, EURO4/RER S	490	tkm	Ecoinvent v2.2
Pellets production	Wood pellets	Wood pellets, u=10%, at storehouse/m3/RER,[3]	7.3	m^3	Modified process
	Transport to household	Small lorry transport, EURO 0,1,2,3,4 mix, 7,5t total weight, 3,3t max payload RER S	1960	tkm	Ecoinvent v2.2
Packing	Process of packing with plastic	Packing, lime products/kg/CH from database Ecoinvent v2.2.[4]	4900	kg	Modified process
Incineration of pellets	Incineration[5]	Heat, wood pellets, at furnace 15kW/SE U[6]	72	GJ	Modified process

1. Original SimaPro 7 process: excavation, skid-steer loader/m3/RER, from database Ecoinvent v2.2. Modified to only including: Lubricating oil, at plant/RER U and Diesel, at regional storage/RER U.
2. Original SimaPro 7 process: Sawdust, Scandinavian softwood (plant-debarked), u=70%, at plant/m3/NORDEL, from database Ecoinvent v2.2. Modified to excluding: Round wood, Scandinavian softwood, under bark, u=70% at forest road/NORDEL U.
3. Original SimaPro 7 process: Wood pellets, u=10%, at storehouse/m3/RER, from database Ecoinvent v2.2. Modified to only including: Electricity, medium voltage, production SE and Wood pellets manufacturing, infrastructure/RER/I U.
4. Original SimaPro 7 process: Packing, lime products/kg/CH from database Ecoinvent v2.2. Modified to only including: Conveyor belt, at plant/RER/I U; Electricity, medium voltage, at grid/SE U; Electricity, hydropower, at run-of-river power plant/CH U; Packaging film, LDPE, at plant/RER U and EUR-flat pallet/RER U from database Ecoinvent v2.2.
5. Energy losses are counted in the last step in SimaPro 7 and the efficiency of the furnace is 82 percent.
6. Change from Swiss electricity to Swedish electricity from database Ecoinvent v2.2.

Appendix 3

Primary data on cultivation and harvesting of Salix from Börjesson (2006)

Table ii Amount of industrial fertilizers needed (per hectare and year) of Salix

Fertilizer	*Amount [kg]*
Nitrogen (N)	64
Phosphorus (P)	7
Potassium (K)	23

Table iii Emissions (per hectare and year) from fertilizing

CO_2 kg	*CO g*	*NO_x g*	*SO_2 g*	*HC g*	*CH_4 g*	*Particles g*	*NH_3 g*	*NO_3^- kg*
280	120	1100	890	80	310	170	2600	15

Table iv Energy required for harvesting (per hectare and year)

Activity	*Primary energy [MJ]*
Harvesting and chipping	1700
Collecting and transporting on field by tractor	530

Table v Emissions (per hectare and year) from harvesting

CO_2 kg	*CO g*	*NO_x g*	*SO_2 g*	*HC g*	*CH_4 g*	*Particles g*	*NH_3 g*	*NO_3^- kg*
180	400	1600	66	140	150	27	0	0

Appendix 4

Data on district heating plant and distribution system from Oliver-Sola, Gabarell and Rieradevall (2009), with some additional changes.

Table vi Components and materials for the district heating plant, the neighbourhood system and the household

Component [unit]	*Material*	*Input process in SimaPro 7*	*Quantity*	*Database*
CHP-plant [1 unit]	Cogen unit 1 MW	cogen unit 1MW, common components for heat+electricity/RER	1 unit	Ecoinvent v2.2
Trench works [1 m]	Pavement	cement, unspecified, at plant/CH	3.84E+01 kg	Ecoinvent v2.2
	Concrete	concrete block, at plant/DE	5.76E+01 kg	Ecoinvent v2.2
	Aggregates	sand, at mine/CH	3.61E+02 kg	Ecoinvent v2.2
	Diesel	diesel, burned in building machine/GLO	3.45E+01 MJ	Ecoinvent v2.2
District Heating Pipes	Steel	steel, low-alloyed, at plant/RER	1.17E+01 kg	Ecoinvent v2.2
	Foamed polyurethane	polyurethane, rigid foam, at plant/RER	2.06E+00 kg	Ecoinvent v2.2
	HDPE	polyethylene, HDPE, granulate, at plant/RER	2.35E+00 kg	Ecoinvent v2.2
Surface box [1 unit]	Water	tap water, at user/RER	2.28E+02 kg	Ecoinvent v2.2
	Sand	sand, at mine/CH	2.08E+03 kg	Ecoinvent v2.2
	Limestone	gypsum plaster board, at plant/CH	1.36E+02 kg	Ecoinvent v2.2
	Cement	cement, unspecified, at plant/CH	4.39E+01 kg	Ecoinvent v2.2

	Cast iron	cast iron, at plant/RER	1.65E+02 kg	Ecoinvent v2.2
	Ceramic brick	brick, at plant/RER	1.79E+03 kg	Ecoinvent v2.2
	Electricity	Electricity, low voltage, production SE, at grid[1]	7.76 MJ	Ecoinvent v2.2
Tap, in main grid [1 unit]	Bronze	bronze, at plant/CH	6.70E-01kg	Ecoinvent v2.2
	Synthetic rubber	silicone product, at plant/RER	6.80E-03 kg	Ecoinvent v2.2
	Cardboard	disposal, packaging cardboard, 19.6% water, to inert material landfill/CH	2.37E-05 kg	Ecoinvent v2.2
Pump [1 unit]	Stainless Steel	Reinforcing steel, at plant[2]	1.51E+01 kg	Ecoinvent v2.2
	Cast iron	cast iron, at plant/RER	1.36E+02 kg	Ecoinvent v2.2
Service pipes [1 m]	Steel	steel, low-alloyed, at plant/RER	3.64E+00 kg	Ecoinvent v2.2
	Foamed polyurethane	polyurethane, rigid foam, at plant/RER	8.20E-01 kg	Ecoinvent v2.2
	HDPE	polyethylene, HDPE, granulate, at plant/RER	1.03E+00 kg	Ecoinvent v2.2
Heat	Galvanized steel	Galvanized steel sheet, at plant[3]	2.27E+01 kg	Ecoinvent v2.2
	Stainless steel	Reinforcing steel, at plant[2]	2.70E+00 kg	Ecoinvent v2.2
	Copper	copper, at regional storage/RER	2.16E+01 kg	Ecoinvent v2.2
	Foamed polyurethane	polyurethane, rigid foam, at plant/RER	2.70E+00 kg	Ecoinvent v2.2

exchanger	PVC	polyvinylchloride, at regional storage/RER	2.70E+00 kg	Ecoinvent v2.2
	Wood	disposal, building, waste wood, untreated, to final disposal/CH	2.70E+00 kg	Ecoinvent v2.2
	LDPE	packaging film, LDPE, at plant/RER	2.70E+00 kg	Ecoinvent v2.2
	Cardboard	disposal, packaging cardboard, 19.6% water, to inert material landfill/CH	3.07E+00 kg	Ecoinvent v2.2

1 Originally for Spain (ES), here changed to Sweden (SE)
2 Originally in report, DE: stainless steel sheet PE (from PE Europe database)
3 Originally in report, DE: steel sheet galvanized PE (from PE Europe database)

Table vii is showing the amount of each component in the distribution system used in the model. Note that all components except the service pipes and the heat exchanger are allocated over 2000 households. The amount for these components here is hence for 2000 households. The amount in the table does not include the division with the expected lifetime of the components.

Table vii Components in the district heating distribution system and their amounts

Component	*Quantity in the scenario*
Trench works	1000 m
District heating pipes	2000 m
Surface box	110 units
Tap	110 units
Pump	20 units
Service pipes	10 m
Heat exchanger	1 unit

Appendix 5

Processes used in SimaPro 7 for district heating with Salix life cycle.

Table viii Processes used for the district heating with Salix life cycle

System process	*Component*	*Input process in SimaPro 7*	*Amount in model*	*Unit*	*Database*
Cultivation of Salix	Fertilizers	Fertilizer (N)	64	kg	LCA Food DK
		Fertilizer (P)	7	kg	LCA Food DK
		Fertilizer (K)	23	kg	LCA Food DK
	Fuel for machine	Diesel, at regional storage/RER U	10	kg	Ecoinvent v2.2
Harvesting of Salix	Fuel for harvesting and chipping	Diesel, at regional storage/RER U	38	kg	Ecoinvent v2.2
	Fuel for tractor for collection	Diesel, at regional storage/RER U	12	kg	Ecoinvent v2.2
	Transport to plant	Transport, lorry 3.5-7.5t, EURO3/RER U	344070	tkm	Ecoinvent v2.2
Incineration of Salix	Incineration	Incineration of wood chips, from forest, softwood, burned in furnace 1000kW/CH U[1]	88.884	GJ	Modified process

1. Original SimaPro 7 process: Wood chips, from forest, softwood, burned in furnace 1000kW/CH U, from database Ecoinvent v2.2. Modified to only including Electricity, low voltage, at grid/SE U, emissions and waste handling.

Appendix 6

Sensitivity analysis results

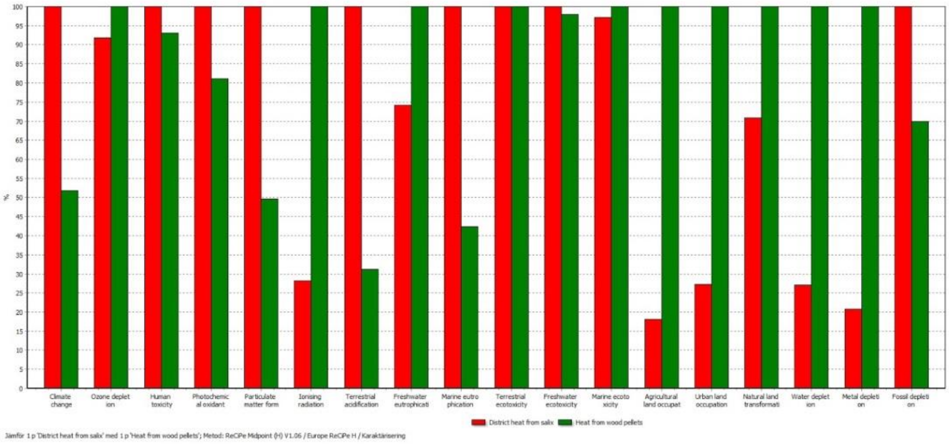

Figure i The result for the altered transport distance between the pellet factory and the household, from 400 km to 10 km, compared with the original district heating from Salix life cycle.

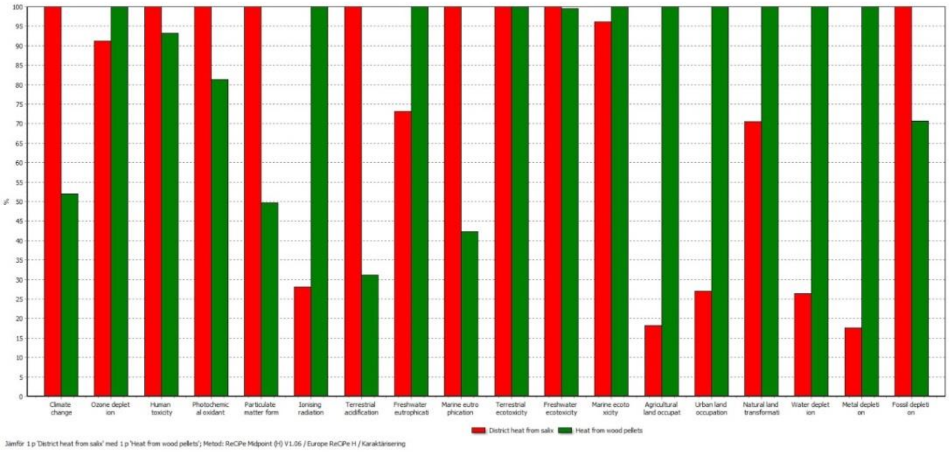

Figure ii The results of the sensitivity analysis with a functional unit of 40 000 kWh.

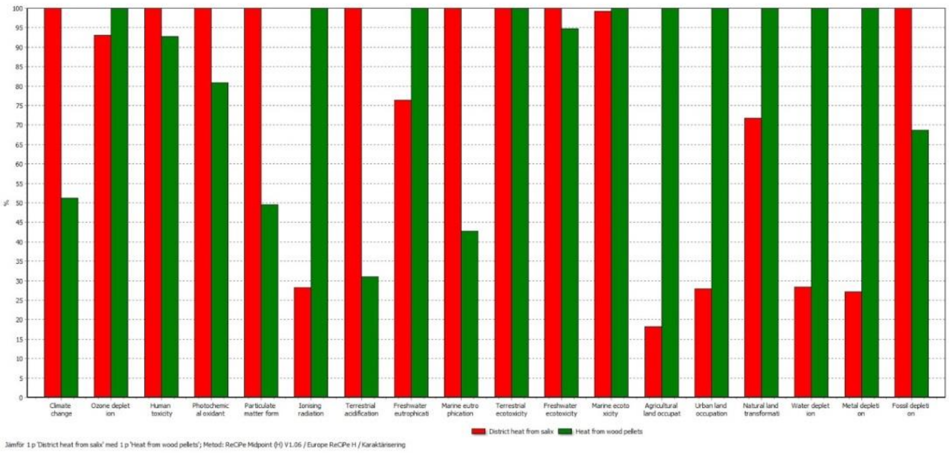

Figure iii The results of a sensitivity analysis with a functional unit of 10 000 kWh.