REPORT

Environmental consequences of different recycling alternatives for wood waste

A report to a Nordic cooperation project on the EC recovery target for construction and demolition waste (CDW)

Martin Erlandsson Jan-Olov Sundquist

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John Munthe
Vice President, Research

ÅFORSK

IVL Swedish Environmental Research Institute

Organization

IVL Swedish Environmental Research Institute Ltd.

Address

P.O. Box 21060
SE-100 31 Stockholm

Telephone

+46 (0)8-598 563 00

Report Summary

Project title

Environmental consequences of EC recovery target for wooden construction and demolition waste (CDW)

Project sponsor

Ångpanneföreningen's Foundation for Research and Development and Foundation (Åforsk, project 12-318) and the Foundation for IVL Swedish Environmental Research Institute (SIVL).

Author

Martin Erlandsson Jan-Olov Sundquist

Title and subtitle of the report

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Summary

The revised framework for waste management in the EU (WFD), adopted in 2008, includes a target for recovery of construction and demolition waste (CDW). The target was added during the final negotiations of the Directive text and was adopted without performing a consequence analysis. In 2014 the WFD target will be evaluated. To provide a basis for assessing the consequences of the target, the Swedish Environmental Protection Agency launched a Nordic project, ENCORT-CDW. This report is a contribution to this Nordic project, funded by Ångpanneföreningen's Foundation for Research and Development and Foundation (Åforsk) and The Foundation for IVL Swedish Environmental Research Institute (SIVL) and tackles the wood CDW.

In Denmark, Norway and Sweden the waste reported as wood waste from the construction sector is mainly incinerated with energy recovery, while in Finland parts of the wood waste from construction may go to incineration without energy recovery or to landfill. However, the present Eurostat data does not reveal if wood waste from construction is re-used or if material is recovered. Consequently, the Eurostat database is not adequate to follow up the WFD target about 70 % recovery. Better information about wood waste flows from "cradle to grave" is required.

The screening LCA performed here uses two system approaches that are applied in LCA: a) the product approach, also known as attributional LCA, and b) consequential LCA covering a complex system. Attributional LCA is very robust and only includes direct consequences, while consequential LCA also includes indirect effects. According to an attributional LCA, which has a product perspective, the use of C&D wood waste for manufacturing of particle board and insulation bats and then substituting gypsum board and mineral wool, will result in environmental improvements. According to a consequential LCA, a marginal fuel has to be defined. This marginal fuel is the fuel that will replace the current C&D wood waste as fuel source. The most environmental profitable alternative will depend on what fuel is assumed to be the marginal fuel.

Keyword

Attributional LCA, consequential LCA, construction and demolition waste (CDW), ENCORT-CDW, life cycle assessment (LCA), recovery target, wood waste.

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Summary from the wood CDW-study

Recovery statistics of wood water (EWC 170201)

Available data from Eurostat states that about 1 206 000 tonnes of non-hazardous wood waste from construction were generated in Denmark, Finland, Norway and Sweden in 2010. In addition, there might be wood waste included in the reported amount of mixed waste from construction, which was about 450 000 tonnes.

According to the Waste Statistics Regulation, all European member states shall report statistics on waste generation and treatment every second year. However, the basis for reporting differs substantially, even between the Nordic countries. The Danish figures are based on data from waste received at registered treatment plants and the Finnish figures are based on waste factors. The Norwegian figures are based on a statistical survey of the municipalities which collect data on construction waste on a yearly basis. Finally, the figures from Sweden are based on a combination of waste factors and a survey of the larger construction companies.

In Denmark, Norway and Sweden the waste reported as wood waste from the construction sector is mainly incinerated with energy recovery, while in Finland parts of the wood waste from construction may go to incineration without energy recovery or to landfill. However, the present Eurostat data does not reveal if wood waste from construction is re-used or if any wood material is recovered. Consequently, the Eurostat database is not adequate to follow up the WFD target about 70 % recovery. Better information about waste flows from “cradle to grave” is required.

Screening LCA

Wood waste from construction and demolition activities may be divided into manufacturing wastage and demolition waste. Manufacturing wood wastage from the construction site may be handled so that contamination and weather exposure is avoided. If so, a pure wood fraction for potential use may be sorted out using a rather simple sorting process. The recycled wood from a demolition site will probably be contaminated in different ways and to a greater extent and needs more processing before use compared to manufacturing wastage. The first target for material recovery should therefore be the manufacturing wastage. This fraction will probably also be less contaminated with wood suffering from biological attack.

The market for recycled wood products was screened in this study in order to identify potential uses that may result in environmental gains. Calculations according to the common ISO standard on LCA (ISO 14044) and European standard on LCA for construction products (EN 15804), showed that wood composite products made of pre-consuming waste (e.g. manufacturing wastage) will not generate any environmental improvements compared to the substitute. Unfortunately, wood products that use cement as a binder (boards and bats) contain too much cement to be useful as substitutes from an environmental point of view. The cement in these products would generate a protection against mould growth. Two wood based products are defined here as interesting alternatives to be produced from C&D wood waste. The first is a particle board which is already produced from such waste in several countries. The second is a wooden insulation product that could be manufactured from recycled wood. The environmental gain can be achieved, when the recycled wood products substitute gypsum board and mineral wool, in such applications where these substitutions are considered to be possible.

The screening LCA was performed using two system approaches: a) the product approach, also known as attributional LCA, and b) consequential LCA covering a complex system. Attributional LCA is very robust and only includes direct consequences, while consequential LCA also includes indirect effects. More information about different system perspectives when performing an attributional or a consequential LCA may be found in Erlandsson et al (2013).

An evaluation that accounts for indirect environmental effects when the C&D wood waste is removed from the current energy market is also performed. In this evaluation it was assumed that the marginal fuel affected by the recovery of C&D wood waste will be forestry residual wood. The consequence of this so-called system expansion includes carbon storage and sinks and the resulting effects on climate change. Such carbon storage is accounted for in the national climate reporting, but there is no full consensus on how such evaluations should be transformed and handled from a product perspective. The calculations made follow the principle given by IPCC and are streamlined by PAS 2050 (that is also used in the Product Environmental Footprint, PEF, as suggested by DG Environment). This indirect effect results in an additional gain, illustrating that material recovery of wood as part of a construction work gives larger environmental gains, compared to the removal of forestry recedes (GROT), which is assumed to be the marginal fuel.

In conclusion, according to an attributional LCA, which has a product perspective, the use of C&D wood waste for manufacturing of particle board and insulation bats and then substituting gypsum board and mineral wool, will result in environmental improvements. According to a consequential LCA, a marginal fuel has to be defined. This marginal fuel is the fuel that will replace the current C&D wood waste as fuel source. Defining the most environmental profitable alternative will depend on which fuel is assumed to be the marginal fuel. The selection of a likely marginal fuel will be different if using a short time perspective compared to a longer time perspective (a few decades). The two extreme alternatives are that the marginal fuel is either any fossil fuel or a bio-based fuel. The first alternative will support that wood should be used for energy recovery and the second alternative that there is a potential environmental gain in wood material recovery.

The market acceptance as well as other technical and non-technical barriers related to the substituting alternatives given here is not part of the study and therefore not accounted for. These issues should be investigated further in future studies

Contents

Introduction

This chapter describes the overall project background goal and limitations.

The revised framework for waste management in the EU (WFD), adopted in 2008, includes a target for recovery of construction and demolition waste (CDW) which reads,

> "by 2020, the preparing for re-use, recycling and other material recovery, including backfilling operations using waste to substitute other materials, of non-hazardous construction and demolition waste excluding naturally occurring material defined in category 17 05 04 in the list of waste shall be increased to a minimum of 70 % by weight." (WFD 2008/98/EC Article 11(2)(b))

The target was added during the final negotiations of the Directive text and thus did not include any consequence analysis. In 2014 the WFD target is to be evaluated.

In order to provide a basis for assessing the consequences of the target, the Swedish Environmental Protection Agency launched a Nordic project, ENCORT-CDW, the results of which is presented in this report. The studies was aimed at resource management and diffuse pollution dispersion related to waste types, which were deemed to have the biggest impact on fulfilling the WFD target on CDW recovery. This report is founded by Ångpanneföreningen's Foundation for Research and Development and Foundation (Åforsk) and IVL Swedish Environmental Research Institute (SIVL) and tackles the wood CDW. The common Nordic report is written by SINTEF, DHI, VTT, SGI and IVL. This report is integrated in the final report from the Nordic project named (published by the Nordic Council of Ministers' (NCM) in the ANP series, Arm el al 2014):

> **Environmental Consequences of the EC Recovery Target for Construction and Demolition Waste — ENCORT-CDW**

The main objective of the project was to provide the Nordic EPAs with a basis for assessing the consequences of the WFD target mentioned above, in terms of resource management and diffuse pollution dispersion. This basis will be used

- when focusing the efforts to achieve a flow of materials from the construction and demolition sector with minimal impact on the environment
- to develop means of control for increased re-use and recycling of C&D waste
- in further discussions with the EC, to give scientific facts to what effects the 70% target in the directive might have in the Nordic countries.

The result will be a written report in the Nordic Council of Ministers' (NCM) ANP series of publication, which provides a basis for summarily assessing the environmental impact of the 70% target in the WFD article 11(2)(b). Contents of the report should be:

- Possible future recovery scenarios and recovery scenarios currently available for a selected set of C&D waste.

- Quantification of the resources saved and the impact on the transports involved for each waste depending on how it is recovered.
- Quantification of the potential spreading of pollutants for each recovery option.

The following prerequisites were set up for the project work:

- The project focuses on mineral construction and demolition waste and on wood waste. It deals with the following recovery operations: re-use, recycling and other material recovery excluding energy recovery (in accordance with the EC target). However, energy recovery is handled for wood waste.
- Hazardous waste and naturally occurring material are not studied (in accordance with the EC target).
- Only impacts of the EC target regarding resource management and spreading of pollutants are handled.
- LCA is only made for wood waste, for the other wastes a "life cycle perspective" is used.
- The LCA for wood waste is a so-called screening LCA covering climate impact, acidification, excessive fertilization, ground-level ozone and energy resource management, but not toxicity for example of wood incineration waste.
- Information and data is collected from databases, literature and personal contacts and, for wood waste, from LCA.
- No laboratory tests are made within the project.

Further prerequisites are given in Decision 2011/753/EU (rules and calculation methods for verifying compliance with the target) which refers to Decision 2000/532/EC (list of wastes and hazardous waste) which is amended in 2001/118/EC, 2001/119/EC and 2001/573/EC.

This wood part differs from the assessment of other materials in this study, since it does not include any leaching estimation but instead includes life cycle assessment (LCA) calculations.

The study includes information from all Nordic countries. The wood waste was studied by IVL. The remaining four institutes, SINTEF, DHI, VTT and SGI, studied all selected wastes in their country.

The project was carried out during 2012 and 2013 by a Nordic project group consisting of the following persons:

Maria Arm (project manager) and Ola Wik SGI, Sweden
Christian J. Engelsen SINTEF, Norway
Martin Erlandsson and Jan-Olov Sundqvist IVL, Sweden
Anke Oberender and Ole Hjelmar DHI, Denmark
Margareta Wahlström VTT, Finland

The project work has been followed by a steering group consisting of:
Henrik Sandström and Erika Nygren, Swedish Environmental Protection Agency
Jon Fonnlid Larsen, Norwegian Environmental Protection Agency
Else Peuranen, Ministry of the Environment, Finland
Metta Wiese, Denmark, has been project manager from the Nordic Council of Ministers.

1 Settings for the wood waste study

Energy recovery through incineration of wood waste is not included in the 70 % target, but frequently used in the Nordic countries. Therefore, the main differences between re-use, material recycling and energy recovery were evaluated by means of collecting national data from the Nordic countries and performing a screening LCA. The screening LCA performed here uses two system approaches that are applied in LCA: a) the product approach, also known as attributional LCA, and b) consequential LCA covering a complex system. Attributional LCA is very robust and only includes direct consequences, while consequential LCA also includes indirect effects. More information about different system perspectives when performing an attributional or a consequential LCA may be found in Erlandsson et al (2013).

2 Impact of the 70% target on the handling of wood waste

This section differs from the assessment of other materials in this study, since it does not include any leaching estimation but instead includes life cycle assessment (LCA) calculations. This different approach is due to the fact that other environmental aspects are of concern regarding recycling of wooden waste.

2.1 National data

2.1.1 Data from Eurostat

Data on wood waste amounts have been obtained from Eurostat's database (Eurostat, 2013). Every second year, all European member states shall report to EU about waste generation and treatment according to the Waste Statistics Regulation (EU, 2002).

The waste generation is reported in 50 different waste categories (named EWC-Stat) and in 19 different sectors. Wood waste is one of the waste categories reported. Wood waste is divided into hazardous wood waste (mainly impregnated wood) and non-hazardous wood waste. Construction is defined as NACE F according to the European economic nomenclature. NACE F[1] is divided into Construction of buildings, Civil engineering, and Specialised construction activities (including demolition).

The waste treatment reporting is divided into the following five categories:
- incineration with heat recovery
- incineration without heat recovery
- recovery operations (excluding energy recovery)
- landfilling

- other disposal.

In the waste treatment reporting there is no connection between generation and treatment, for example the statistics do not show how the wood waste from construction is treated, only how the wood waste from all sectors in general is treated.

The data reported for the year 2010 is presented in Table 1.

Table 1 Generation of non-hazardous wood waste from construction, reported in 2010 (Eurostat[2], 2013).

Country	**Wood waste** *(tonnes)*
Denmark	20 641
Finland	891 000
Norway	169 201
Sweden	125 000

There is no Eurostat data on the treatment of wood waste from construction, nor from any other sector. Treatment data is only available for all wood waste from all economic sectors. The data on the treatment of non-hazardous wood waste from all economic sectors for 2010 is presented in Table 2.

Table 2Treatment of non-hazardous wood waste from all economic sectors in 2010 (tonnes). (Eurostat[3], 2013).

	Total waste treatment	Incineration / energy recovery (R1)	Recovery other than energy recovery	Incineration / disposal (D10)	Disposal
Denmark	**129 196**	10 631	116 762	0	1 803
Finland	**10 445 832**	7 630 000	2 795 000	15 140	5 692
Norway	**426 514**	4 057	323 080	61 155	38 222
Sweden	**1 413 833**	1 320 459	93 317	0	57

Some comments on these figures on generation and treatment are presented in the following.

2.1.2 Denmark

The Eurostat database shows a rather small amount of wood waste generated compared to the other Nordic countries and also compared to data from earlier years (Denmark reported 226 754 tonnes of wood waste from construction in 2008 and 8 185 tonnes from waste collection). For 2010 some 21 097 tonnes are reported as generation of wood waste from construction. For the same year, about 289 687 tonnes are reported as generation of wood waste from other waste collection.

Data from the Danish EPA's waste database (Danish EPA, 2013)[4], which is based on data from the ISAG system (data from waste received at registered treatment plants) indicates that the amount of wood waste from the construction sector was 63 415 tonnes in 2009. Denmark is currently updating the waste registration and newer data is not obtainable for the moment. The following treatment of wood waste in 2010 is reported in Eurostat for Denmark:

- Total treatment of wood waste: ca. 149 567 tonnes
- Incineration/energy recovery 18 715 tonnes
- Recovery other than energy recovery 125 953 tonnes
- Disposal 4 899 tonnes

The treatment of the wood waste is not presented, but probably nearly all wood waste from construction is treated by energy recovery.

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2.1.3 Finland

The figures from Finland are based on waste factors (based on construction statistics). The same figures are also presented at Statistics Finland's website (Statistics Finland, 2013). The amount seems to be high compared to the other Nordic countries.

There are no reports about the treatment of wood wastes from construction in particular, only on the treatment of wood waste from all sectors. The total treatment of wood wastes from all sectors amounts to 10.5 million tonnes, of which 21% is recycled (wood residues from saw mills), 76% is energy recovered, 1.4% is incinerated without energy recovery and 2.4% (about 250 000 tonnes) is landfilled. It is likely that some of the landfilled wood waste originates from constructions.

2.1.4 Norway

The figures from Norway are based on a statistical survey of the municipalities which collect annual data on waste from construction. In 2011 the amount had increased to 228 345 tonnes (Statistics Norway, 2013)[5]. According to Statistics Norway 226 917 tonnes of wood waste from construction is incinerated whereas the treatment of the remaining 1 428 tonnes is not specified.

The major part of the total wood waste from all sectors is either energy recovered or recycled, but small amounts are also either landfilled or incinerated without energy recovery.

2.2 Screening LCA

2.2.1 The origin of the waste matters

The environmental benefits of recycling will vary depending on the origin of the waste. In statistics the waste source is not always known, as mentioned above. In this context, when the goal is to evaluate environmental aspects, it is interesting to know if the waste origins from an old discarded product or if it is actually a production residue. These two alternatives may be defined as follows[6]:

- *Pre-consumer* materials are generated by manufacturers and processors, and may consist of scrap, trimmings and other production residues that were never used on the consumer market.
- *Post-consumer* material is an end product that has completed its life cycle as a consumer item and would otherwise have been disposed of as a solid waste. Products made from "post-consumer" materials implies that the material origins from the society (from the techno sphere resource pool) and not directly from a natural resource.

With respect to the environmental burden in any system analytic tool, pre-consumer materials have to take some responsibility for the environmental impact from the process that it origins from – even though it might be very small depending on the principle of the allocation procedure used. Inapproachable of the allocation procedure used, the well-established international standard for LCA (ISO 14044) sets that an inherent property may never be allocated away. Examples of such inherent properties are inherent energy content or the fact that the material is made of bio-based raw materials.

The term "post-consumer materials" means that the historical environmental burden has already happened and is allocated to the first or previous product system using the raw material as such. In a so-called attributional[7] LCA – the methodological approach regarded as the most robust way of performing an LCA – the historical impact is treated as a sunken cost[8] and the only "problem" left is to define the system boundary when the first product life cycle ends and the new one starts. A common way to do this is to follow "the lowest value of interest[9]". So, when the scrapped product is sold as a waste material its forthcoming environmental impact will be allocated to the new product system. This definition may vary between countries and in some cases also regionally. If a producer of a recycled product gets paid to "take care" of the wood waste, it is only the environmental impact from this point that will be allocated to the recycled product system. Note that even in this case, when an allocation is performed in accordance with the ISO 14044 main stepwise allocation procedure, the energy efficiency for *e.g.* district heating may be as low as 1 (but not less). This is a fact since the upstream energy use is allocated to the original product system, but the inherent energy content is not possible to allocate "away" and the environmental burden will follow the waste used as fuel.

The principle of "the lowest value of interest" is included in the new guideline for environmental construction products (EN 15804) which is related to CPR. However, it is overruled by the fact that energy recovery has to meet at least an energy efficiency of 60% (as defined in the waste directive). Consequently, all energy recovery processes with efficiency better than 60%, are defined as energy processes, and the waste used will then have an environmental upstream impact and resource consumption at least equal with the inherent mass. All district heating plants in northern Europe are by this definition energy processes and the delivered energy will have an environmental impact from the combustion etc. This means that the energy delivered from such plants will have an environmental burden and the waste is not responsible for the environmental impact from the combustion process. Therefore, this kind of analytic figures based on basic natural science assumption shall not be compared to those simplified approaches referred to as so-called primary energy factors that also include elements of on value choices (i.e. subjective).

2.2.2 Basic assumptions for setting the scenarios

Re-use

There are no official statistics in the Nordic countries on the re-use of wood products from the construction sector. It is assumed that the re-used amount is insignificant, even though we notice that products with antique values actually have a place on the market like old doors, iron ovens and windows and may be re-used[10]. Moreover, the realism in an increased re-use of wood products is low but theoretically possible. In the waste context of interest here, re-use may then be regarded as a waste prevention strategy. However, since we assume that this will only cover a minimal part of the wood waste flow we do not consider this alternative further. In the long run also these re-used products will become wood waste and have to be treated properly from an environmental perspective. Re-use is therefore not an interesting alternative for this study.

Pre-consumer recycling

The basis for the present analysis is construction waste, thus, the wood waste that appear in the manufacturing of *e.g.* sawn timber is not regarded as construction waste (compare with the Finnish statistics above). It could be disputed if the production residue from sawmills should be regarded as waste at all, since most of the wood residues from sawmills are actually sold as raw materials.

The (only) wood waste that falls into this group is scrap wood from construction sites and different construction activities during the life cycle of construction works. This scrap wood has the potential to be sorted at the construction site and divided into different fractions suitable for further processing. Furthermore, it is dry and normally free from mould and rot.

To achieve an environmental gain, it will help if the fact that the material as such is already dried is used to save energy in the further processing. Currently, such dried wood scrap is *e.g.* used by the wood pellets industry. However, since that opportunity is part of energy recovery it falls outside the target recycling products that we seek for here. Instead, different wood composite products could be interesting. Scrap wood could be used for bio-based wood/plastic composites commercially available on the market today (*e.g.* deck and terrace material), However, these composites typically utilise pre-consumer plastic waste, thus the environmental gain is not as beneficial as if post-consumer waste had been used. The commercial development of non-renewable binders is therefore an alternative for wood composite products to achieve a more favourable environmental performance. The use of bio-based binders is potentially possible but not an economical realistic alternative today. These kinds of products will therefore not be evaluated further.

Other boards like plywood, OSB and LVL are not applicable since they require solid wood as resource. MDF and HDF boards include wet processing steps (such as the Masonite-method). More interesting is if a dry process was used instead and should then imply to any larger environmental gains. It was not found any running manufacturing equipment for production of insulation material based on a dry process. Therefore, due to lack of environmental or process data[11], the environmental performance could not be evaluated.

The only commercially available product made of recycled wood scrap identified here (besides the one mentioned above) is particle board. The fact that the scrap wood itself normally will have a lower moister content than 20% (water/dry mass) makes it a resource efficient alternative compared to the use of virgin wood that first has to be dried and the scrapped product is thus a perfect raw material for particle boards. Particle boards might also substitute other boards made of gypsum, silica, cement etc.

In theory, it should be possible to defibrate, i.e. to mechanical breakdown, the wood chips together with pressurized steam into wood fibrous components opposed to the method mention above. This kind of waste wood fibres produced from the defibrator method (also known as the Asplund method) should be possible to use as raw material for cellulose based insulation materials. This approach is a suggested innovation and does not exist and therefore has to be evaluated here from an environmental point of view rather than a technical (that might be interesting based on the environmental evaluation).

Post-consumer recycling

Post-consumer recycling means that the wood is aged and the inherent properties are changed. Perhaps the most problematic is if the wood is biological contaminated. The most promising products listed above are particle boards and insulation materials. In the latter case the product is often treated with fire retardants like boron (borax and boric acid). There are other fire retardants, but from a wood preservative perspective it should be known that these boron additives are efficient against mould and fungi as well. Boron is not used as wood preservative outdoors or in ground contact since it leaches too easy, but it is used as wood preservative indoors or in applications where the products are not exposed to weathering. For this case study, we will assume that it is possible to sort and store the discarded wood for the use as raw material in a particle board, without adding any chemical treatment to resist biological attacks. When used in insulation material it is common to add fungicide and fire retardants. In the case of recycling wood that is mechanically broken down in the size of saw dust or wood chips, 5% by weight of calcium hydroxide ($Ca(OH)_2$ slaked lime) has historically been added to resist biological attacks. In literature it is mentioned that in Germany that cement is used for the same purpose.

Cement bound products are interesting as the combined cement-wood mixture resists biological attack. The products available are boards and wood wool manufactured for plaster base, building elements (with wood reinforcement), sheet for removable false ceilings and for wall cladding. The products consist of wood wool or particles, cement and water. The products consist of 70 to 90% by weight of cement and therefore have difficulties to compete with more wooden based products, thus these products are not accounted for here.

In conclusion, particle board is one of the most realistic alternatives for recycling of wood scrap and discarded wood material. One manufacturing technique is that the recycled wood is used in the the particle board centre while the surface is made of virgin wood. This type of board is illustrated in Figure 1 and will guarantee an attractive wooden colour of the surface. Different machinery that may use recycled wood as raw material was found, such as Fransson's Recycling machines (www.Franssons.com). Another machinery producer had experienced that it may cause problem when recycled wood is used, and that sorting is important. A test production of particle boards made of recycled wood was set up based on experience from Norway but had to close after half a year due to too much contamination that caused problem for the milling machinery[12].

Figure 1 Particle board made of waste wood

2.2.3 Selected products and functional unit

Based on the current knowledge, two products are selected as target for the case study to be manufactured with recycled wood as raw material. These products are particle boards and a wooden based insulation material. These two product groups are investigated and compared to a market dominant product that they might substitute.

The comparisons are made for 1 m^2 of board or insulation material with the same functional performance. In both cases this means that the thickness of the board materials may vary, and also the insulation slab thickness[13], in order to achieve a functional performance. By experience and regarding the usable intended use of these evaluated products, the products' service lives are assumed to be equal and no maintenance is needed for either product group. This product-to-product route will make it easy to compare individual product alternatives in a life cycle perspective, without any assumptions on service life predictions.

Moreover, the analyse in this case study is dived in two scopes as follows;

- product perspective
- societal perspective

The product perspective is found on an attributional life cycle perspective, meaning that a univocal result is achieved, since minimal methodology settings are needed according to the so-called core product category rule (PCR) EN 15804. Another benefit with attributional life cycle perspective is that the environmental impact reflects consequences in the real world, and thus the impact may be compared with national statistics like climate reporting etc.

The analysis then takes a societal scope into account. First, the individual saving is evaluated for a product which is substituted with a bio-based product. The attributional LCA approach is applied in this evaluation. The societal level is included by taking the annual savings into account. Then, the calculation requires knowledge on the market volume of the substituted product (and that the bio-based alternative with recycled wood can fulfil the functional requirements). Since the attributional system perspective is used, only *direct effects* are included, i.e. only the product perspective is accounted for. A second alternative evaluation is then set up where also *indirect effects* related to the foreground system is analysed. The foreground system defines the part of the expanded product system that in the society is actually affected by the changed manufacturing alternatives analysed. In this case, the foreground system includes the scrap wood that is currently used as energy carrier for district heating and then will be taken away. This energy system has to make use of a new alternative energy source – ***a margin fuel*** – that is the next energy source when the energy market is expanded and the old sources are insufficient.

The potential margin fuel that most likely will be explored in the future is forestry residues, also called primary forest fuel and including branches and tree tops ("GROT"), stem wood and stumps. Forestry residues are already used today, but the extraction can increase and will probably be used further in the future. Large investments in new district heating plants in Sweden have that in common that the plants are designed to use bio-based fuel like forestry residues[14]. This waste is a pre-consumer waste. The "Heat plan Denmark" also take into account a significantly increased amount of biomass. Moreover, in the current market situation, the additional biomass extracted from the forestry will be used as a fuel instead of, as in many parts of the forestry today, just left at the harvesting site. It is assumed here that the biomass from the forestry will be the main new marginal biomass based fuel. The forestry residual wood will not, according to this scenario and in the context of LCA, be a waste but a commodity with a market value. In theory, these kind of secondary effects do not necessary stop at the foreground system, but also affect other linked product systems that share a common (margin) market. This kind of secondary effects beyond the foreground system is not accounted for here and is a common limitation in this kind of so-called system expansions.

As complement to the basis scenario given above, a sensitivity scenario is introduced where waste is assumed to be the margin fuel. Oil or any other fossil fuel is not regarded as a realistic alternative and is only used to describe 'What if', and may represent a historical perspective for district heating. In the short time perspective it is likely that waste actually will be the marginal fuel if there is no biomass. In the calculations, an environmental performance of 20 g CO_2/MJ[15] is set for an average waste fraction used in the district heating. This figure then represents a fuel that consists of about ¼ of fossil resources. In the current "Heat plan Denmark", waste can actually be regarded as a marginal waste. The same kind of scenario is found for Sweden. However, a number of political actions is likely to take force when the waste in the long run most likely will increase and in a Swedish scenario the waste amount will therefore likely peak around 2030. Danish policy goals[16] support this development, *e.g.* the (material) recycling of household waste should increase from the current 22% to 50% in 2022, and organic waste from the service sector should go from 17% today to 60% in 2018. In the context of wood and wood waste from the construction sector, the wood cycle in this kind of application will be from 30 to 50 years or even longer if parts of the building or other structural parts are included.

2.2.4 Consequences in the product perspective

Two product groups are included, namely boards and insulation, as potential future products that may be produced from recycled wood. Note that other products may exist and the study do not claim that the selected alternatives handled here is the only alternatives or the best suitable alternatives. The alternatives included here shall be regarded as examples.

Insulation products environmental performance – attributional LCA

Mineral wool is the dominant insulation material on the Swedish market followed by cellular plastic (EPS, XPS) and cellulose fibre (made from recycled paper or virgin paper pulp). Mineral wool is dived in stone wool and glass wool. Stone wool is here used as reference product for the environmental calculations performed.

Wood from recycled construction products may be sorted into manufacturing wastage and demolition waste. Manufacturing wood wastage from the construction site may be handled so that contamination and weather exposure is avoided. If so, a pure wood fraction may be sorted out that can be used at the site to produce *e.g.* cutting shaving that may be recycled and installed in the very same construction works. Such cutting machinery exists and may be used for a local production of cutter shavings[17]. The question is, however, what volumes that may be generated of this virgin wood pure waste. A more prefabricated construction sector should reduce this amount of manufacturing wastage. This cutting shaving and saw dust is by tradition mixed with calcium hydroxide or cement that also can be added on site. Saw dust is produced by cutting, and a product with relative high density is crushed wood from wood waste may be produced by a hammer crusher, or less sensitive mill technique. No measured data on the thermal quality for these fractions was found, but we have assumed a relative high λ value (assumed values for cutter shaving and sawdust/wood chips is set to 0.044 and 0.08 W/mK respectively), why these alternatives are not so resource efficient.

In old houses a porous wood board was commonly used for insulation (known as *e.g.* Tretex). Modern versions of this product exist and are not limited to thin boards (<300 mm) but also thicker rigid boards by gluing a number of board (typically by using PCAc)[18]. The use of this kind of rigid board is assumed to be a minor market share compared to other insulation products like flexible bats. More interesting is an insulation production of a rigid or more preferable flexible wooden bat. Such products exist and may use a wet process[19] or a dry process[20]. The identified machinery manufacturer for the dry process was contacted, but did not answer about *e.g.* energy need etc. for running the process or if it is installed anywhere. It could be assumed that the dry process is more energy efficient and more tolerant in the mechanical processing; crushing, sorting and a final milling of the perhaps contaminated wood. In the calculations below, data for a wet process is used in lack of data from the dry process. It should be noticed that a dry process requires a resin since the lignin cannot be utilised in the same way as in a wet process.

In order to make a fair comparison between different insulation alternatives a functional unit that takes an equal thermal quality into account is used. This implies that the different material will have the same thermal resistance (R=0.2). This equal resistance is calculated based on the material specific so-called lambda value, λ. In practice this means that that 200 mm stone wool shall be compared to 400 mm of saw dust. An average density for stone wool is set to 30 kg/m^3 and 320 kg/m^3 for saw dust, which means that it requires a huge amount of saw dust to reach the same thermal quality. Cutter shaving, on the contrary, has a low density (about 65 kg/m^3) and better λ value. This means that saw dust will not give any environmental gains compared to if cutter shavings were used instead of stone wool (Table 3).

Table 3 Environmental performance reported as cradle-to-gate LCA data and an equal resource use per m2 to achieve an equal functionality. This equal functionality is based on an equal thermal resistance, R, of 0.2 m2·K/W.

Product alternatives	kg/m^2	$kg\ CO_2\ e/m^2$	Relative insulation quality
Stone wool	6	7 159	1.00
Cutter shavings	14	709	1.13
Insolation board (Pavatex) [a]	28	11 508	1.03
Saw dust	128	6 211	2.05
Flexible Wood Fibre Insulation boards (Feelingwood) [a]	8	2 900	0.97

[a] The environmental impact is based on the manufacturing process using virgin resources, why the impact is over estimated compared to if recycled wood was used instead.

Data for stone wool is based on an EPD from Rockwool in Norway. LCA data reported from other sources is in the same range.

The LCA data for a porous wood insulation board (Pavex) originates from one producer in Germany. It includes different additives and is based on a wet process. Moreover, the data is based on primary resources and therefore the environmental impact should be lower if based on recycled wood. This fact is also valid for the flexible wood fibre board (Feelingwood). The data from Flexible wood is also based on a combination of different sources based on a specific recipe valid for Feelingwood. The data for the wood wool is data from Karlit and their (former) production of porous wood boards (the plant is closed down). The environmental impact for a polyolefin (PE, PP etc.) that is used for binders and ammonium polyphosphate[21] is added and the latter works as a fire-retardant. This latter data is based on generic data from Ecoinvent (a LCA database). The LCA data for cutter shaving and saw dust includes the mechanical treatment of wood and the calcium hydroxide (note that if data for cement was used, the impact would be reduced a bit).

Based on the result in Table 8-4 it can be concluded that – if possible in practice – the shaving cutting as insulation material is the most environmental preferable. Obstacles concerning the economy for manufacturing of this product, small volumes and cheap material direct from the construction or demolition site make this product a more theoretical alternative than a practical one. Moreover, the product is a loose fill product why the intended use is limited. The low density flexible wood insulation bats are therefore more promising alternatives to compete with stone wool. The low environmental impact is generated by a lower density that also gives a better λ value. The porous wood insulation board will be a competitive alternative in applications such as wind breaking insulation (in the external part of the wall construction inside the facade material.

Cladding boards environmental performance – attributional LCA

Gypsum is the dominant wall cladding board on the market. The inherent property of gypsum gives it added value for sound insulation (heavy mass) and for fire protection. The weak aspect is that it risks suffering from mould attacks and potential fastening of different elements. Gypsum is easy to cut and easy to give a final plane finish over the board laps, which gives it added values in the construction process. As an educated guess, 2/3 of the interior walls are made out of single gypsum boards and 1/3 with double layer (or even triple in some occasions). Double layer increase the fire resistance, sound insulation and fastening possibilities. In the walls with double layers it is common to use OSB (oriented stain board), plywood or particle board to increase the potential fastening possibilities. Since these boards require more work to get plain over board laps etc. it is regarded as more cost effective to add an extra layer of gypsum board, instead of (most likely) just a layer of particle board. In this latter case we may assume that if only increased fastening is aimed at two layer of gypsum board will be equal with one layer of particle board (with an equal thickness).

In order to have an equal comparison we will assume that one standard gypsum board with a nominal thickness of 12.5 to 13 mm is equal to a 12 mm particle board. An average density of 650 kg/m^3 is set for the particle board and 720 kg/m^3 for the gypsum board, respectively. The functional unit will be an equal cladding board 12 mm gypsum board in standard application without requirement on heavily fastening. This functional unit may be regarded as in favour to gypsum board, but in remind that 2/3 are single boards applications, it seems justified for most applications.

The resulting environmental impact for gypsum board and particle board is listed in Table 8-5. No environmental data was found in the literature concerning manufacturing of recycled wood particle board. As basis for the calculation of a traditional particle board, LCA data from the end of the nineties is used and reported above as "STD particle board". In those days, it was still common to use oil for thermal energy supply. This fact is changed nowadays. Moreover, the environmental profile for the STD particle board is made from wood from sawmills, and following EN 15804, it means that this post-consumer waste has an environmental backpack, which will not be the case as if construction waste was used instead. Therefore, these figures have been recalculated to reflect a manufacturing where wood is used for thermal energy and wood waste is used as raw material. This will definitely improve the environmental performance of the recycled wood particle board, which is reported in Table 4.

Table 4 Environmental performance reported as cradle-to-gate LCA data and an equal resource use per m^2 cladding board

Product alternatives	kg / m^2	g CO_2 / m^2
Gypsum board	9.0	1 990
Recycled wood particle board	7.8	1 201
STD particle board	7.8	2 129

The LCA data for gypsum board is from a producer that uses 99% gypsum waste as raw material (as we understand the allocation approach in this LCA, all gypsum waste used is regarded as free of environmental loads). Therefore, the gypsum board is regarded as a top of the line version, but is used here since it is likely that other producer will follow this trend. The recycled particle board is the most profitable alternative concerning environmental impact contribution to climate change. As mentioned above, but worth repeating, different wood composite products will not imply an improved environmental performance that may compete with gypsum board, as long as pre-consumer plastic waste is used as raw material. Recycled particle board is a product that exist on some markets and has a relative low environmental performance why this is a strong candidate to potentially replace gypsum board for some extent. It should however be kept in mind that this requires a domestic manufacturing and not transport from abroad, which will increase the environmental impact of the recycled particle board.

2.2.5 Result on the societal level – attributional LCA

What is the potential national savings in Sweden if recycled wood from the construction sector is partly used to manufacture wooden based insulation bats and cladding boards and then replaces stone wool and gypsum boards?

The Swedish insulation market has a turnover of about 3.5 to 4 million m^3 (Mm^3) per year[22]. 60% to 65% of this market is mineral wool, 25% is cellular plastic and the remaining part is dominated by cellulose fibre[22]. These figures, together with the assumption that 2/3 of the mineral wool market share is substituted with wooden insulation bats made from recycled wood from the construction industry, will result in a yearly production of 61 kton. The remaining 1/3 comprises construction solutions where insulation boards cannot meet the required properties. From environmental performance and thermal quality figures reported in Table 5, the savings from shifting from mineral wool (represented here by figures on stone wool) will lead to a yearly saving of 52 kton CO_2e. It shall be noticed that the savings are much larger if cutter shavings were substituting mineral wool for some portion. However, technical issues concerning the possibility to actually use construction manufacturing waste as raw material, together with questions marks concerning the economy for this manufacturing process have to be investigated further before this alternative could be seen as a realistic potential substitute. The potential savings related to this option are, however, very interesting to explore more in depth in the future.

The Swedish gypsum board market is dominated by Knauf Danogips and Gyproc that together have a market share of about 70% (in 2012) of a yearly total turnover of about 38 million m^2 (Mm^2). As mentioned above, 2/3 of the market is assumed to be single layer gypsum boards. In the remaining 1/3 it assumed that another 1/3 is double layer gypsum boards that might be substituted with particle boards. The remaining part is applications where gypsum board has properties that do not make particle boards as a potential alternative or other materials such as OSB and plywood is used. Altogether this means that 31 Mm^2 recycled particle board can be manufactured substituting gypsum board. Based on the figures in Table 5, a yearly potential saving of 25 CO_2e kton is possible to reach.

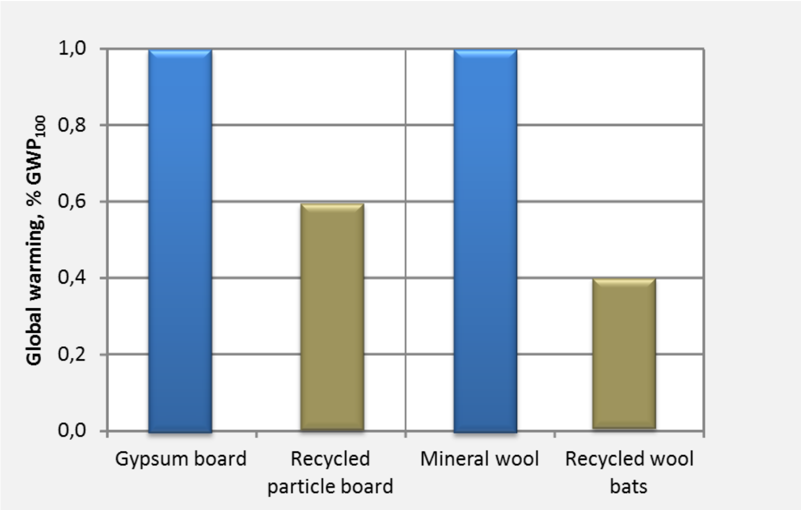

Figure 2 **Relative impact related to global warming, when producing 1 m^2 board or insulation bats, comparing wooden product made of C&D waste and normalized to the potential substituting products. The difference, and therefore the potential saving when substituting, is equal to the difference between the blue and the brown bar.**

In Figure 2 the most assumed realistic substitutes given in Tables 4 and 5 are summarized. The difference between the current product (blue bars) and the wooden product made of C&D waste (brown bars) is reported per square meter.

2.2.6 Marginal approach for product substitution – consequential LCA

Secondary effects are analysed in a consequential LCA. The case of future recycling of wood waste from the construction sector, which previously was used as fuel in district heating plants, will affect the district heating plants fuel mix. The evaluation performed here is divided in two parts; first, potential consequences of biotic carbon and temporary carbon sink effects are accounted for, second, the environmental margin consequence is calculated when different margin fuels are assumed. This effect is analysed with a so-called system expansion as illustrated in Figure 3. Note that the calculations are independent of the moisture content in different energy wares, since the combustion plant is supposed to be equipped with flue gas condensation. This is a common technique today, both in municipal solid waste fired plants and in bio-based fired plants.

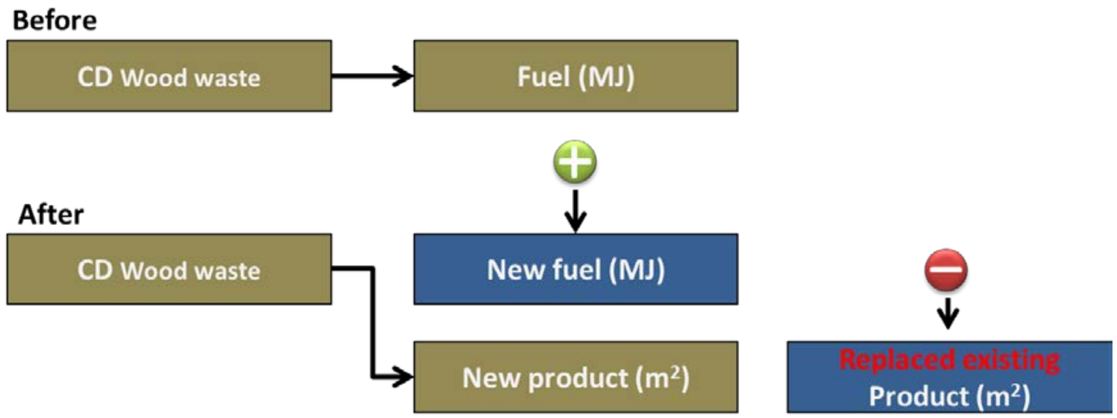

Figure 3 The principle of "system expansion" takes indirect effects into account by adding the consequences from the new fuel and the replaced existing product resulting in a marginal effect. Note that the "remaining"' or more correct "equal comparable" complex function after system expansion is an equal amount of fuel. The calculated resulting negative figure is called "avoided emissions".

Biotic carbon and temporary carbon sink

This scenario describes the case when the wood waste from the construction sector is used in new construction products and the carbon fixed in these products will result in a delayed emission, compared to if the waste was used for district heating. On the other hand, additional harvested forestry wood waste, which before harvesting was biodegraded in a few decades, will now be emitted directly after harvesting in the district heating plant combustion process. An exponential approach is set up to model this biodegrading of biomass on the ground, where almost all biomass is supposed to be emitted within 50 years (Figure 4).

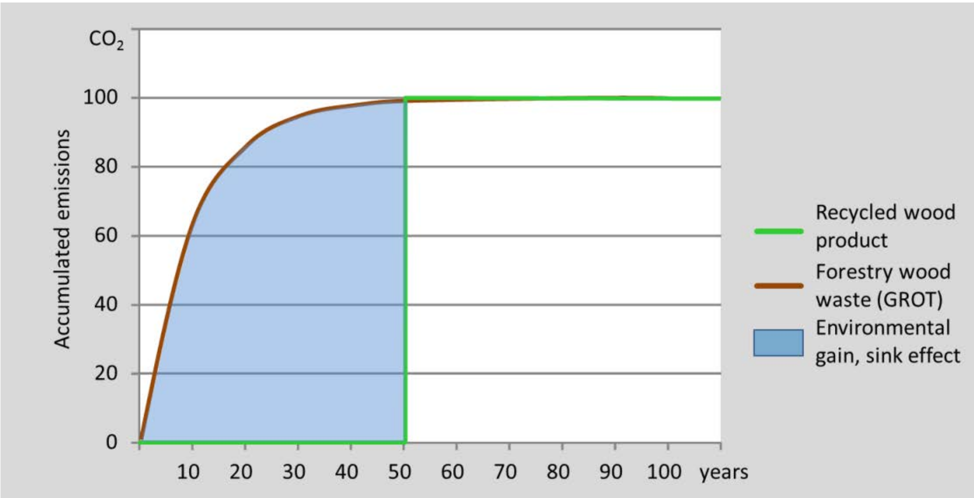

Figure 4 Accumulated emission scenario for a) construction wood waste that will be used as raw material for a new wood product and stored in construction works for 50 years, and b) forestry residues that now will be used as replacement fuel at the district heating plant.

In LCA, the time horizon boundary cut-off is normally set to 100 years and this is also the case for setting the integrated effect when calculating the impact assessment factors for climate change. If one accepts this boundary condition, the effect of a sink or delayed emission can be estimated based on the same underlying equation as given by IPCC[23]. The approach used here follows the British standard for climate footprint calculation named PAS 2050. Equation 8a below is the same that is suggested by ILCD handbook (JRC, 2010) as method for the so-called Product Environmental Footprint (PEF), which is commissioned by DG Environment. This weighting factor, WF, is calculated as (PAS 2050:2011):

$$WF=(\Sigma\, p\cdot(100-i))/100 \tag{8a}$$

where

WF is the weighting factor

i is each year in which emissions occur

p is the proportion of the total emissions occurring in any year *i*.

The wooden product in the scenario calculations is assumed to be stored in construction works for 50 years and then emitted. When the emission scenarios (Figure 4) are combined with equation 8a to model delayed emissions, the impact of 1 kg CO_2e from wood waste stored in a building for 50 years will be equal to a positive contribution to climate change of 0.5 kg CO_2e/kg, The, so to say, “lost storage” of forestry residues from harvesting and thinning is a negative consequence that will be allocated to the environmental burden to the new recycled product made of wood waste from the construction sector. This sink effect accounts for the “lost storage” (see Figure 3), where more than 80% of the wood has transformed to carbon dioxide by natural processes and according to equation 8a has generated a sink effect of 0.16 kg CO_2e/kg. This will result in a net positive contribution of 0.34 kg CO_2e/kg recycled wood, in favour to the recycled C&D waste product. With other words; the sink effect from the storage wood in the construction works has greater positive effects than the negative aspects from taken forestry residues as a new fuel to the district heating plant. If the wood is stored for 100 years (or longer) the net benefit will increase to 0.84 kg CO_2e/kg recycled wood. However, as mentioned above, this kind of calculation is not general agreed upon and is not part of the mandatory impact categories in EN 15804. Nevertheless, if such sink effect is accounted for, it will gain the material recycling alternative.

It should be noticed that the way to calculate the effect from a carbon sink may be disputed and is not given as a default indicator in EN 15804. Therefore, the figures given here in this matter shall only be regarded as an indicator of the sink effect. The evaluation of the sink effect is based on the assumption that the emission credit of a sink is limited to 100 years, and will then be in line with the time horizon as for the GWP 100 years, used to assess the value of emitted greenhouse gases.

Consequence on system expansion and different marginal fuels
A future recycling of wood waste from the construction sector will have consequences on the fuel market. This wood waste was previously used as fuel in district heating plants and the changed use will therefore affect the district heating plants fuel mix. As argued above, in the base scenario, the margin fuel in an expanding fuel market relevant for district heating plants is assumed to be forestry residues. This additional potential fuel is not economical to harvest today, but we assume that it will be in the future. For a sensitivity analysis it is assumed that a generic waste fraction that generates 20 g CO_2/MJ is the margin fuel. The environmental impact from combustion of the same amount of recycled wood is assumed to be the same as if forestry residues were combusted. This assumption seems to be fair concerning contribution to climate change. Moreover, for the case study we assume that the same handling and transportation is carried out (equal to 150 km road transport from source to storage and then to the district heating plant). Furthermore, emission of biotic carbon dioxide is in this kind of calculations set to zero for all resources originating from a sustainable silviculture (the forestry management). Therefore, the potential difference in fuel quality will not be visual when comparing different bio-based fuels. It is now possible to calculate the impact from the recycling, see Figure 5.

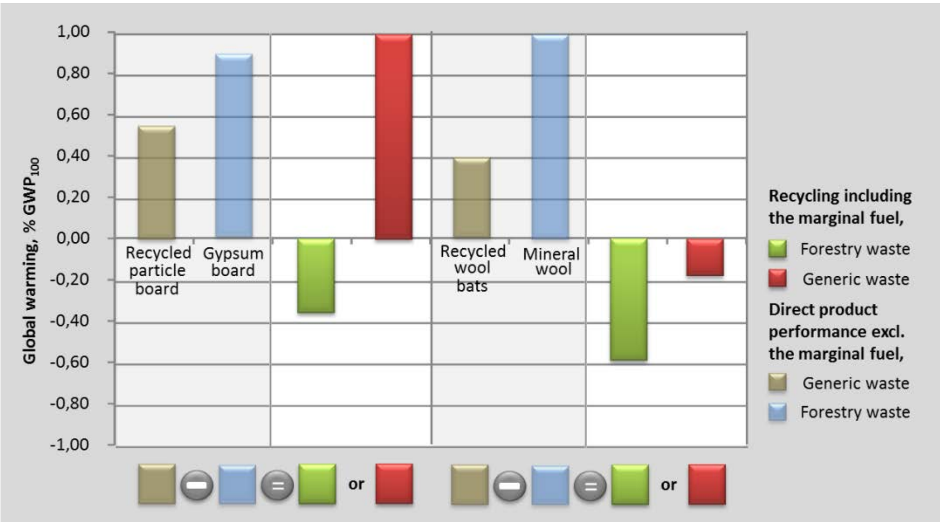

Figure 5 Environmental savings from material recycling when producing 1 m^2 board (left) or insulation bats (right) made of C&D wood waste and substituting forestry waste (green bars) and generic waste (red bars). The contribution to global warming is normalized to the largest value for respective material scenario. Both the source data (transparent blue and brown bars) and the resulting potential savings (green and red bars) from the system expansion are included in the same figure.

The result when performing a consequential LCA is typically dependent on which marginal fuel that is selected. In this case, when the marginal fuel is a biomass product, the material recycling route will be gained (see green bars in Figure 5). In this case, the attributional and consequential LCA system perspective gives the same result. If a generic waste fraction is assumed as marginal fuel, the energy recovery will be more profitable than producing particle board (see left part of Figure 5 and red bar that generate a larger avoided emission indicating that energy recovery in this case is the favourable alternative). However, in the case of material recycling for a wooden insulation product, the material recycling route will be the most profitable alternative, inapproachable if the marginal fuel is forestry waste or a generic waste.

If fossil fuels like oil or coal was the margin fuel, this would support the energy recovery route in both cases. In the very short run, this assessment indicates that energy recovery is the overall preferable route, as long as a fossil fuel is the marginal fuel. In the case that the marginal fuel is a waste fraction that contains about ¼ of material with a fossil origin, the most preferable recycling rout depends on what substitute that is analysed. It should be noticed that current waste as an average includes around 50% fossil CO_2 emissions[24, 25]. Also in future is it likely that up to 40% of the average waste fraction in district heating includes fossil materials[26]. If these references are used, based on the result in Figure 5, it will lead to the conclusion that material recycling and the wood bats in this case are not the preferable route. Based on the two wooden based products investigated here, a tipping point between energy recovery and material recycling seems to appear when a waste fuel with a fossil carbon content around 20% is the substitute that replace the C&D wood waste. However, in the long run when the district heating probably will be almost fossil free and biomass is the marginal fuel, the material recycling route has the potential to be the better alternative. When dealing with the future, it is also technically possible to increase the use of bio-based fuels in the manufacturing of stone wool and therefore replace the coal used. Such development will generate an improved profile for stone wool, but is not accounted for here.

This study included environmental consequences in respect to global warming. Other aspects are not considered and should require a more extensive work. In respect to toxicity it is for instance interesting to evaluate if it is accepted that non-hazardous wood waste is suited for material recovery, even if it can contain paint with zinc, lead etc.

3. Discussion and conclusions

3.1 Main conclusions

Although the recycling statistics are uncertain, it can be concluded that the present recovery rate of asphalt and track ballast waste is well above 70% in the Nordic countries. These materials represent large material flows, but at the moment they are generally not included in the Nordic waste statistics. Considering their high re-use or recycling rate, including or excluding them will highly influence the opportunities of attaining the WFD target of 70% recovery.

The following main conclusions are established from the common Nordic project (Arm at al 2014), which state that the EU recovery target does not ensure a sustainable waste recovery in its present form since it,

- **favours recycling of high density waste types**. The result is that mineral wastes will have the largest impact while the largest environmental benefits might be on other waste types.

- **does not favour the most sustainable recovery operations.** Above all, it does not distinguish between backfilling and other more resource efficient recovery operations. Since backfilling is a recovery option that generally results in both low benefits and future environmental risks, this increases the risk for "down cycling", which means that the waste is not recovered in the most optimal way.

- **is very sensitive to interpretations of what is considered as waste and waste recovery**. This fact is significant, since the WFD definitions of waste recovery actions such as re-use or recycling, are mainly aimed at the building construction field and does not fit well with materials recovered within other construction fields. As an example, asphalt and track ballast, which represent large material flows with a high re-use or recycling rate, are generally not included in the waste statistics and this will highly influence the interpretation of attaining the target.

Therefore, the following recommendations are given regarding the EU recovery target:

- Transform the general weight based target into waste specific targets. This would favour recycling of CDW in general and not only for high weight materials.

- Rank the recovery operations in the calculation method for reporting progress. Backfilling should not be regarded as equal to other operations for recovery.

Furthermore, we recommend the Nordic countries to:

- **Improve the knowledge of waste flows and waste handling** in order to monitor progress regarding a sustainable CDW recovery. This is crucial since the current Eurostat waste data quality is low. It does not allow an assessment of resources saved, environmental benefits gained or potential environmental risks. One example is that statistics on mineral materials with high grade re-use or recycling options are often reported merged with low grade mixed mineral wastes and contaminated wastes. Another example is that statistical data does not distinguish between contaminated (painted) wood and pure wood suitable for material recovery.

- **Set up national recovery targets and management measures** so that the most effective recycling pathways are promoted and those posing the biggest environmental risk are avoided. National targets should be waste specific and operation specific, promotion should be done through facilitation of favourable options in technical specifications, guidelines and regulations and finally, prevention of undesired operations should be done through environmental quality criteria.

High quality recycling is promoted if the waste fractions are successfully separated and there is a system for quality assessment and declaration of the waste fractions produced.

- **Improve the knowledge of pollution contents of CDW and emissions associated with the recycling**. A substantial share of CDW exceeds (the more or less applicable) environmental criteria. Available data, however, contains significant gaps due to scarce data, biased data, outdated information and inadequate or poorly documented sampling and measurement methods. To enable better assessment of environmental risk than currently possible, harmonized monitoring methods and collection of data are needed. This is a suitable area for Nordic cooperation.

- **Promote recycling of wood waste in new construction materials.** At present, wood waste is mainly incinerated with energy recovery, but there is a large opportunity for reducing the Global Warming Potential if material recovery is increased. However, further knowledge about technical and environmental obstacles and possibilities is required.

Some differences between the Nordic countries justify recovery targets and management measures tailored to national circumstances. However, there are also many similarities which make an increased exchange of knowledge on waste properties, risk assessment and management measures advantageous. A common approach also creates improved opportunities for the Nordic countries to influence European legislation.

3.2 Environmental consequences from wood CDW study

Significant environmental improvements are potentially possible if construction and demolition wood waste (C&D wood waste) is material recycled. An initial screening of such potential recycling was performed in this study and this novel assessment indicated that the environmental gain is possible taking existing technically feasible products like particle board and different wooden insulation products into account. However, the work did not cover economic aspects, *e.g.* if this is commercially possible under current market situations. An educated guess is that the manufacturing of the recycled wood products is only possible if the wood waste is free of charge for the building material industry and if the wood is sorted in a quality suited for the recycling purpose. Furthermore, the calculations made presume that the transport distance will be about the same as today, which means that the production of the recycled wood product has to take place domestically or in a neighbouring country.

The assessment performed used two systems that are applied in LCA: a) the product approach, also known as attributional LCA, and b) consequential LCA covering a complex system. Attributional LCA is very robust and only includes direct consequences, while consequential LCA also includes indirect effects. More information about different system perspectives when performing an attributional or a consequential LCA may be found in Erlandsson et al. (2013).

An evaluation that also accounts for indirect environmental effects when the C&D wood waste is removed from the current energy market was also performed. This evaluation assumed that the marginal fuel affected by the recycling of C&D wood waste will be forestry residual wood. The consequences of this, so-called system expansion, includes the carbon storage and the sink effect and their effects on climate change. Such carbon storage is accounted for in the national climate reporting, but there is not full consensus on how such evaluations should be transformed and handled from a product perspective. The calculations made, follow the principle given by IPCC and are streamlined by PAS 2050 (that is also used in the Product Environmental Footprint, PEF, as suggested by DG Environment). This indirect effect results in an additional gain, illustrating that material recycling of wood as part of a construction work gives larger environmental gains, compared to the removal of forestry recedes (GROT), which is assumed to be the marginal fuel.

In conclusion, according to an attributional LCA, which has a product perspective, the use of C&D wood waste for manufacturing of particle board and insulation bats and then substituting gypsum board and mineral wool, will result in environmental improvements. According to a consequential LCA, a marginal fuel has to be defined. This marginal fuel is the fuel that will replace the current C&D wood waste. The most environmental profitable alternative will depend on what fuel is assumed to be the marginal fuel. The selection of a likely marginal fuel will be different if using a short time perspective compared to a longer time perspective (a few decades). The two extreme alternatives are that the marginal fuel is either any fossil fuel or a bio-based fuel. The first alternative will support that wood should be used for energy recovery and the second alternative that there is a potential environmental gain in wood material recycling.

The market acceptance and other technical as well as non-technical barriers related to the substituting alternatives given here is not part of the study and therefore not accounted for. These issues should be investigated further in future studies.

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Notes

[1] NACE = Nomenclature générale des Activités économique dans les Communautés Européennes
[2] http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/data/database accessed 2013-09-30
[3] http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/data/database, accessed 2013-09-30
[4] Danish EPA. (2013). Waste statistics accessed in December 2013 (in Danish): http://www.mst.dk/Virksomhed_og_myndighed/Affald/Tal_for_affald/Statistikker_og_ISAG-dataudtraek/

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[6] http://www.feeneyarchitectural.com/feeneyarch/LEED/pop_LEED.html
[7] Attributional LCA = a study where each product has a given environmental burden based on allocation rules. The system is characterized of the 100% rule meaning that if this LCA approach is used the environmental burden related to all product consumed will match what is actually emitted in the real world. This is also why this LCA approach also sometimes is called book keeping LCA and is a methodology that is frequently used for EPD (environmental product declaration). An alternative or supplement is as a consequential LCA study where the difference between two alternatives are analyzed and following the difference between these alternatives are reported. This LCA approach requires scenario setting that strongly affects the outcome of the study.
[8] Meaning that all historical impact will be regarded as zero and not allocated to the product under study.
[9] The delineation between two product systems is considered to be the point where the waste has its "lowest market value". This means that the generator of the waste has to carry the full environmental impact until the point in the product´s life cycle where the waste is transported to a scrap yard or gate of a waste processing plant (collection site).
[10] http://www.ircow.eu/media/downloads/D%205.1%20(v2)_%20DP_%20Report%20on%20CS1%20and%20CS2.pdf
[11] http://www.siempelkamp.com/index.php?id=800
[12] Personal communication 2013-09-02, Bo.E Sjöberg, BO-E. SJÖBERG i Stockholm AB
[13] An equal thermal comfort is taken into account based on the current λ value. The λ value describes the thermal conductivity that is equal with the rate at which heat is transmitted through a material, measured in Watts per square metre of surface area for a temperature gradient of one Kelvin per metre thickness, simplified to W/mK. The lower λ value, the better the thermal efficiency of the material.
[14] Våra bränslen. Söderenergi AB, 2010.
[15] Current figures for household waste in Sweden are about 30 to 40% based on: Bestämning av fossilt kol o avfall som förbränns i Sverige. Avfall Sverige, rapport U2012:02.
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[17] http://www.sjoberg-jonkoping.com/stallstro.htm

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[18] http://www.kalcer.si/iz_pavatex/Prospekt_Pavatex.pdf

[19] http://swedish.hunton.no/assets/webbilder/brosjyrer/hunton_flex/Flex__produktark_low_feb_2010_Nyadress.pdf

[20] http://www.siempelkamp.com/fileadmin/media/Englisch/MaschinenundAnlagen/prospekte/Siempelkamp_wood-fiber_insulation_board-eng.pdf

[21] Ammonium polyphosphate is also used as a food additive and emulsifier (E number: E545).

[22] http://www.viivilla.se/Energi/Spartips/Isolera-ratt---och-spar-pengar-42820

[23] See: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html and the note concerning estimating the CO_2 response function that is based on the revised version of the Bern Carbon cycle model (Bern2.5CC; Joos et al. 2001)

[24] Bestämning av andel fossilt kol i avfall som förbränns i Sverige. Rapport U2012:02, ISSN 1103-4092. Avfall Sverige 2012.

[25] Analys av den fossila andelen av norskt avfall med hänsyn till energiinnehåll. Profu, Göteborg 2006-05-05.

[26] Färdplan 2050 El- och fjärrvärmeproduktion. Rapport ER 2012:30 2012, Energimyndigheten 2012