Lóránt Sándor Katona-Farnas

Analysis of energy recovery options of combustible demolition waste

Helsinki Metropolia University of Applied Sciences

Bachelor of Engineering

Degree Programme in Environmental Engineering

Bachelor’s Thesis

May 2017

Author(s) Title Number of Pages Date	Lóránt Sándor Katona-Farnas Analysis of energy recovery options of combustible demolition waste 55 pages + 5 appendices 26 May 2017
Degree	Bachelor of Engineering
Degree Programme	Environmental Engineering
Specialisation option	Renewable Energy Technology
Instructor(s)	Antti Tohka, Title (Senior Lecturer, Metropolia University of Applied Sciences)

Construction and Demolition Waste represents approximately one fourth of the total solid waste generated inside the European Union. Its proper management is a key issue due to the EU recycling target, rising raw material prices and landfill space scarcity. The most desirable management options are the re-use, material recycling, energy recovery and eventually landfilling. However, prioritization can be neglected if there are sufficient evidence that originally less desirable options can bring more environmental benefits.

This thesis aimed to analyse different waste management options for the combustible fraction of demolition waste, with emphasize on energy recovery technologies. The chosen technologies were the combustion with energy recovery and gasification. A simplified Life Cycle Analysis has been carried out in order to ease the comparison of these technologies in the case of two buildings situated in the Great Helsinki area, that are going to be demolished. The system boundaries include transportation and the selected thermochemical treatments. Two different scenarios have been built up, one with mainly wood containing demolition waste and the second having as subject mixed demolition waste based on fossil carbon. Three environmental impacts and energy recovery have been included in the analysis. Calculations were based on emission limit values, average energy content of certain materials, and assumptions. Results of the analysis should be treated by keeping in mind the uncertainty about the data quality, the amount of assumptions and the site-specific nature of study.

The results of the analysis show that each technology and the accompanying logistics have their advantages and drawbacks. Plant efficiency plays a dominant role in energy recovery, meanwhile transportation distance has its own important share in environmental burdens. Final decision regarding the most suitable energy recovery technology for demolition waste should be based on factors such as distance between demolition site and waste treatment facilities, composition, quality, level of contamination and energy content of the waste. Further data collection and studies are needed lower the uncertainty of the results and to facilitate the decision making.

Keywords	Demolition Waste Management, energy recovery from combustible demolition waste, LCA of combustible demolition waste

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Terms and Abbreviations/Glossary

BAT	Best Available Techniques
BREF	Best Available Techniques Reference Document
C&D waste	Construction and Demolition Waste
DW	Demolition Waste
CHP	Combined Heat and Power Plant
EMS	Environmental Management System
EU	European Union
kW	Kilowatt
LCA	Lifecycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MSW	Municipal Solid Waste
NCV	Net Calorific Value
Recycling	Different processes with the aim to convert waste into useful materials
Reuse	The use of waste or used product without reprocessing
RDF	Refuse-Derived Fuel
SRF	Solid Recovered Fuel
WtE	Waste to Energy
wt. %	Weight %

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1 Introduction

The way as we treat our waste is in change due to more and more strict regulations but also due rising landfilling prices, and cost of raw materials and energy. While in developed countries the transition from landfilling to selective waste collection and recycling is fully developed or at least it is in final implementation phase, developing and undeveloped countries are yet landfilling their waste or are at an early stage of development.

1.1 Legal framework

Inside the European Union, the Waste Framework Directive from 2008 specifies the main aspects which should be followed in the national waste chain management. This guidance sets up also the priority order of waste management preference as follows: prevention, (preparing for) reuse, recycling, other recovery, and disposal being the least desired option.

1.2 Background

The quantity of the waste the humanity produces grows year after year. A large part of this waste comes from the construction industry. It has been estimated that about 25 % of the waste generated comes from construction and demolition. In many countries Construction and Demolition Waste have risen due to urbanisation, however in others, mainly developed western countries, the trend is to renovate and extend the life of old buildings. Considering that about half of all natural resources extracted yearly in Europe, are used in the fabrication of construction materials, it is understandable the concern and current focus on the Construction and Demolition Waste (C&DW) generation and management. [1]

Until recently, C&DW has been considered to have no substantial negative impact on the environment or human health, and its management has been confined to landfilling it. In the last years, this attitude slowly has been changed for many reasons. Firstly, we should mention the increasingly stringent regulations regarding waste management. Secondly a large part of this waste could be easily recycled or re-used, rather than being simply dumped into landfills, depleting the already meagre available landfill areas that we have. Thirdly, many materials are contaminated therefore they require proper waste treatment and management. Last, but not least construction and Demolition Waste can be energy carrier thereby, from the power production industry point of view, it can be considered as possible raw material.

1.3 Justification of the thesis

The EU Waste Framework Directive sets up a 70 % recycling target for non-hazardous Construction and Demolition Waste by 2020. [2] In some EU countries, the target has been already achieved meanwhile in others a systematic waste management approach is needed to accomplish the goal. Finland, having a wood bases construction legacy, phases big challenge to fulfil the EU requirements, because energy recovery is located on an inferior level in the waste management hierarchy. However, the same directive states that in cases where it can be proved that inferior waste management option brings more environmental benefits or cause less environmental burdens.

1.4 Goal and scope of the thesis

The aim of this thesis is to contribute to the decision making regarding combustible Demolition Waste management options at two buildings, planned to be demolished, in the Helsinki Metropolitan Area. The goal was to analyse energy recovery potential of two waste-to-energy technologies and to compare their environmental burdens together with accompanying transportation. One of the considered options was the incineration with energy recovery at WtE power plant located in Vantaa, the second option being the gasification of Demolition Waste followed by combustion of generated syngas at Kymijärvi II Lahti power station.

To facilitate the comparison of these two thermochemical treatments and associated transportations of the waste from the sites to the waste treatment plants, a simplified Life-Cycle Assessment (LCA) had been conducted. As functional unit, the “energy recovery of 1 tonne solid waste” was chosen and the system boundaries include logistics (transportation, pre-treatment of Demolition Waste), thermal conversion processes, but does not consider bottom and fly ash handling, neither final disposal of them.

2 Methodology

2.1 Legal framework

The EU's and Finland's nationally waste management regulatory framework was shortly reviewed. The emphasize had been put on directives regarding Construction and Demolition Waste management and waste transportation.

2.2 Construction and Demolition Waste data review in EU and Finland

This review part seeks to provide a general overview about amount and type of waste generated during construction and demolition works. Demolition Waste (DW) has been highlighted since the aim of this thesis is to analyse solutions and environmental impacts of different DW management techniques with emphasize on combustible fraction. Figure 1, gives us an image about the share of C&DW and makes it understandable why its correct management is so vital both virgin material and environmental wise.

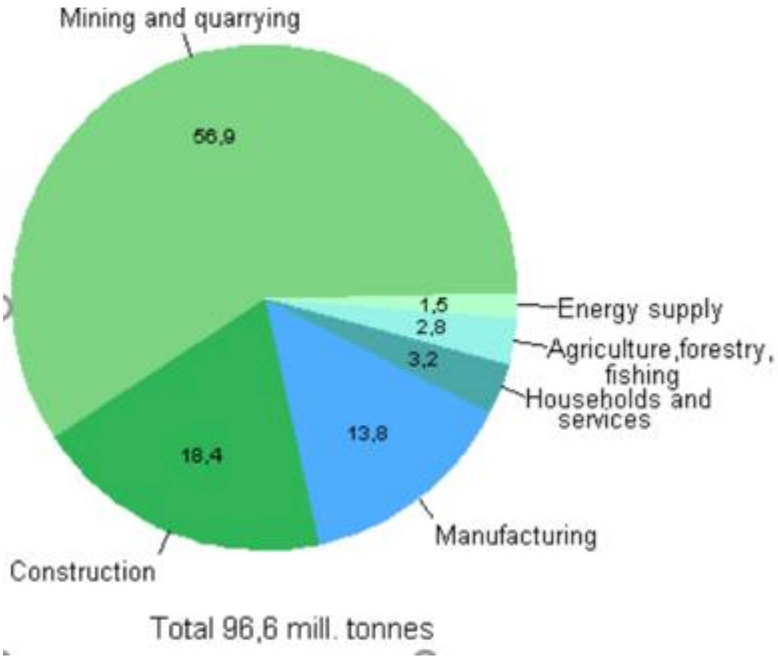


Figure 1. Amounts of waste by sector in Finland 2011 [3]

2.3 Stakeholder identification

A range of stakeholders were identified and the key organisations were highlighted.

- Waste generators
- Waste transporters
- Reprocessing facilities
- Energy recovery power plants
- Landfills i.e. disposal sites

2.4 Demolition and energy recovery process description

Short description of demolition and waste treatment (mainly thermochemical energy recovery) techniques. Two distinctive demolition techniques were considered, the conventional which is more mechanical and restrict the segregation process, and the combined which integrates the selective, primarily manual deconstruction and the mechanical demolition. During manual deconstruction, i.e. disassembly both the potentially hazardous components and very clean parts of the building are removed, while during mechanical demolition, the generated waste goes to the mixed waste container which afterwards is taken to further treatment.

3 Construction and Demolition Waste

The Construction and Demolition Waste (C&D waste) definition is widely used for waste which has been created during construction, renovation, or demolition of a building or any construction structure (bridge, road). In most of the cases there is no clear distinction between waste coming from new constructions and waste from renovations or demolitions. This fact is true also in Finland’s case. Even though quantity of C&D waste was somehow monitored, clear regulation or legislation regarding the recycling or reuse of C&D waste has not been in force. The only restriction in respect of landfilling of C&D waste was related to its hazardous or non-hazardous nature.

The composition of the C&D waste is diverse, including mainly concrete, bricks, tiles, mortar, ceramics, wood, metals, plastics, gypsum, and others some of them classified as dangerous substances like asbestos, PCB, PAH, or lead based paints. [4] However different countries have different ways of defining what it is considered construction or Demolition Waste. There are countries where soil is considered construction waste meanwhile in others it is not included in statistics. The European Union Waste Framework Directive 2008/98/EC refers as waste any material or product that is going to be discarded by holders. [5]

3.1.1 Legal framework of C&D waste management in Finland

Waste management practices in Finland are regulated by national legislation which largely follows the EU legislation. The legislative framework regarding C&DW is based on the following acts:

- Waste Act 646/2011
- Government Decree on Waste 179/2012
- Land use and building Act 132/1999
- Land use and building Decree 859/1999
- Environmental Protection Act 527/2014
- Environmental protection Decree 713/2014
- Government Decree concerning the recovery of certain wastes in earth construction 591/2006 [6]

According to the Government Decree on Waste (2012)

> *'construction and Demolition Waste* means waste from new construction and repairs and demolition of buildings or other fixed structures, civil engineering work or other corresponding construction'
> [7, Section 1]

Based on the same document, companies engaged in construction or demolition projects have the obligation to make a separate collection of C&D waste to facilitate recycling, recovery or other treatment. Furthermore, requires that all usable parts are reclaimed and re-used. [7, Section 15] Special care is required for asbestos waste.

Transportation of the waste should be done in a manner that no waste is released into the environment. In Section 16 the minimum sorting requirements define the main waste types as follow:

- Concrete, brick, mineral tile and ceramic waste types
- Gypsum-based waste
- No-impregnated wood waste

- Metal waste
- Glass waste
- Plastic waste
- Paper and cardboard waste
- Soil and waste rock material

3.2 Constituents of Construction and Demolition Waste

Based on the European Union (EU) Waste Framework Directive [2] waste classification, soil that cannot be reused onsite or as aggregate in roads, it will be classified as C&DW. While during construction and renovation the amount of waste is relatively modest, demolition of old buildings produces large volumes of waste. Values regarding quantity and composition of the C&DW show high geographical variations. These variations are unfortunately also due to poor solid waste management practices and levels of control and reporting [4]. Some countries lack completely data about C&D waste, and most probably the waste ends up in landfills or illegal dumps. However, some estimations have been done based on national statistical data concerning demolition of old buildings and questionnaires. These estimations are far to be accurate but they can give an approximate idea about the quantity of C&DW generated, which is estimated to be just in the EU somewhere between 800-1000 million tonnes per year. [8] A breakdown of generated waste amount based on economic activities can be seen in Figure 1.

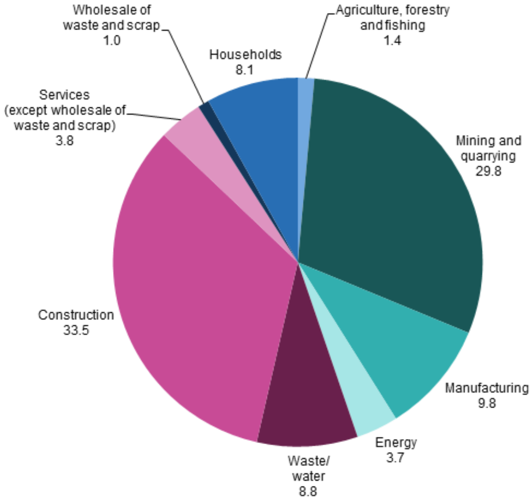


Figure2. Waste generation by economic activities [8]

Based on data published by Eurostat Waste statistic section, construction and Demolition Waste accounts to about one third of the total waste generated in the European Union. Because of its huge amount, C&D waste became a priority waste stream in the European Union. The objective of the EU is that up to 70% of the C&D waste (by weight) should be recycled, reused or undergo material recovery.

Because C&D waste management is only in its infancy, detailed data about the composition of waste is rarely available even in developed countries. The composition of C&D waste is dependent on construction typology in specific areas. In some areas wood is the preferred construction material (see Finland), meanwhile in others concrete or bricks are the dominant construction materials.

3.3 Construction and Demolition Waste in Finland

3.3.1 Quantity and quality of C&DW in Finland

Quantity and quality of C&DW generated in Finland varies from year to year and depends mainly on factors like economic situation, social-demographic evaluation, etc. Waste generated by construction industry falls in certain categories based on material composition. The main categories and the associated amounts can be seen in Table 1. Unfortunately, waste generated during construction and demolition works are registered together, therefore a distinction between these two is impossible.

Table 1. Amount and waste types generated by the construction industry [3]

Type of waste	**2011 (1000 tonnes)**	**2012 (1000 tonnes)**
Mineral	17815	15682
Metallic waste	265	78
Glass waste	1	1
Paper and cardboard waste	6	5
Plastic and rubber waste	0	14
Wood waste	253	238
Sludges	14	0
Household and mixed waste	70	5

In Figure 3. It can be clearly seen that wood generally represents one of the dominant waste fraction, and its yearly variation is almost insignificant. Disregarding soil waste, in 2013 approximately 224000 tonnes of construction waste had been generated, out of which about 63% was wood waste. [9]

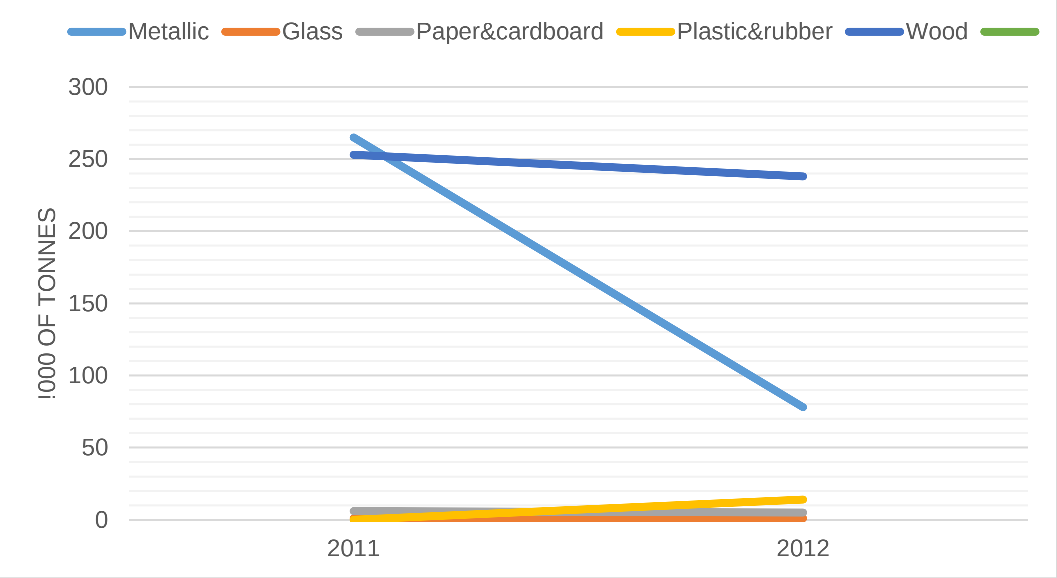


Figure 3. Amount of construction waste generated in 2011 and 2012 [10]

As we can see in Figure 4. the dominant waste fraction is the mineral because it includes heavy soil materials resulting from excavation. If we remove the mineral waste the situation is completely changed.

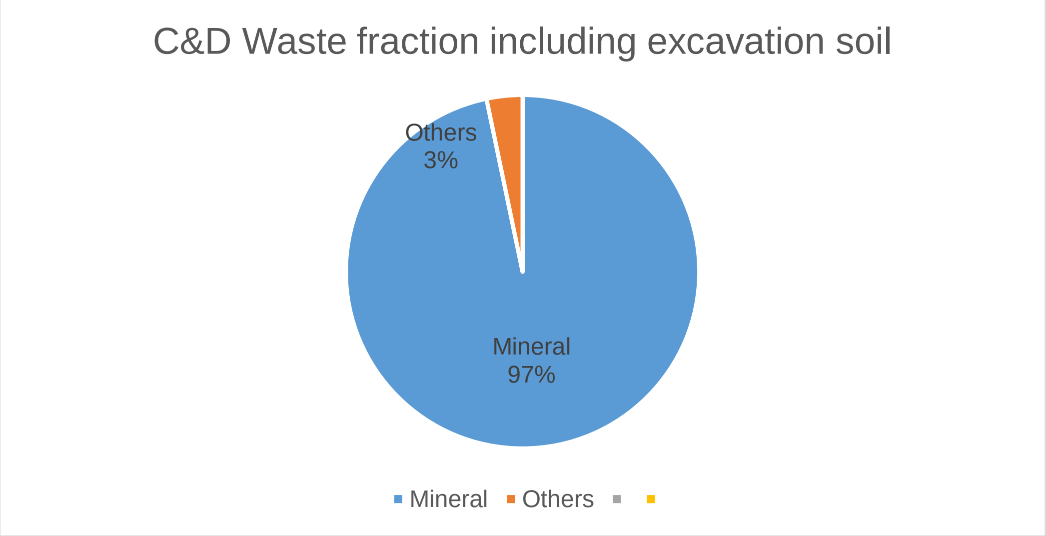


Figure 4. Components of C&D waste in 2011 [3]

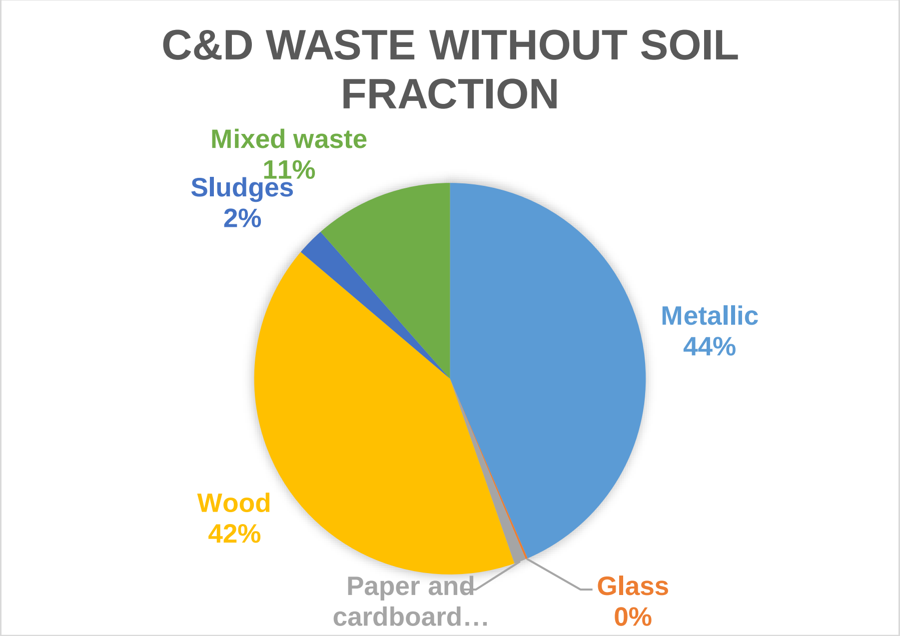


Figure 5. C&D waste in 2011 without soil fraction

4 Logistics and Demolition Waste management plan

The operational chain for Demolition Waste can be divided in three phases: generation of the waste, recycling processes and final utilisation of the recycled waste. Each section comprises some sub-sections like materials, technologies involved, services, and stakeholders. A visualisation of this structure can be seen in Figure 5.

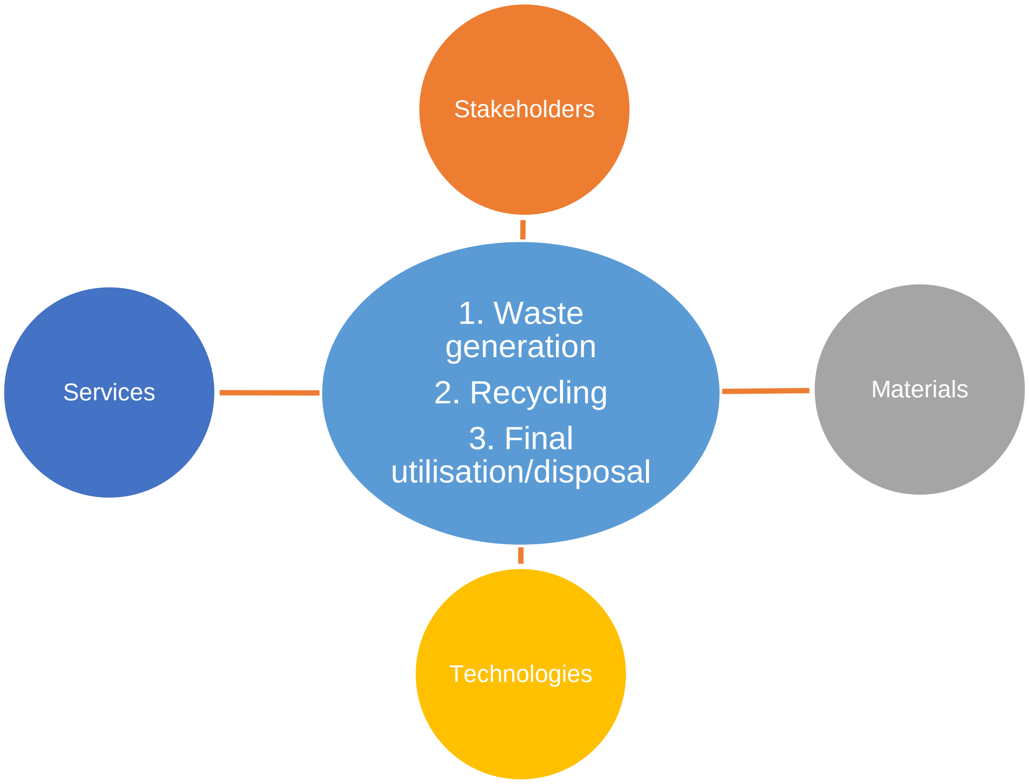


Figure 6. Operational chain for Demolition Waste

Material part tells us about the kind of waste fractions that have been generated, fractions that have been recycled and rejected, and finally their classification as final products.

In the technologies subsection, we define the technologies involved in segregation, recycling and final use phases. In the first phase, waste is generated by mechanical and manual demolition and segregated in the aforementioned ways. Nowadays, manual segregation is crucial to disassembly and remove electrical equipment which can be reused, sold or recycled.

Generally, there is an onsite segregation where the main fractions of waste are separated from mixture. After onsite segregation, different waste fractions are transported to recycling facilities. In the recycling facilities, certain technologies such like: further sorting, crushing, separation of recovered materials and rejects, mechanical processing and incineration are applied to the incoming waste stream.

In the last phase, namely utilisation of recovered waste materials, technologies involved are the manufacturing and energy recovery ones, where the recovered waste fractions are reused as raw materials for new products and in the latter, they go through a thermochemical process where energy content of the waste is recovered.

Stakeholders are all companies or organizations that are involved in the C&D waste generation, recycling or are final users of the recycled materials. [11]

4.1 Before demolition

Demolition of buildings can be conducted in two main ways, namely selectively or in conventional way. If a selective demolition is carried out, then re-use of materials is more likely possible than is case of conventional demolition when recycling or energy recoveries are the only possible steps before landfilling. Usually conventional demolition is implemented by mechanized methods (e.g. excavator, hydraulic hammer, etc.) or using explosives without any prior disassembly. In contrast, during selective demolition material is dismantled from buildings into different fractions.

4.1.1 Estimation of the amount and type of waste

A proper estimation of the type and amount of waste that is going to be generated is crucial, to achieve an efficient and sustainable waste management. A good estimation helps both time scheduling, waste storage and transportation processes. Before demolition work, an environmental inventory should be carried out to investigate whether the building contains any hazardous materials that must be removed or treated before demolition work starts. [12]

4.1.2 Identification of waste streams

Identification of all possible waste streams that are likely to be generated

The number of waste streams vary in function of demolition technique applied and extent of segregation. If the goal is to recycle as much as possible out of recyclable C&D waste than a selective demolition should be applied. This technique increases the rate of recyclability but also the cost of demolition is increased. As the number of waste fractions increases the storage and transportation cost escalate. The main recyclable C&D waste fractions, disregarding soil, concrete, metal and bricks, are uncontaminated wood, plastics, insulating materials, and plasterboards.

4.1.3 Segregation of waste

Proper segregation increases the quality of recycled material thereby the profitability of material recovery is supported. Degree of separation should be based on available options and on an analysis of the costs and revenues of separated materials. [13]
A good segregation plan follows the following basic guidelines:

- Reuse - maximize the amount
- Recycling - maximize the amount
- Disposal at authorized waste facilities - minimize the amount

4.1.4 On-site planning and organization

A good material recovery is achieved if employees are well prepared and trained professionals, who understand how the waste management will work. A good understanding about the importance of segregation and pollution prevention are ineluctable for sustainable demolition processes. Well-grounded knowledge helps both employees in their daily work and management to maintain quality. Well organized waste collection system on demolition sites are more aesthetical, easy to use, safe, and not least strengthen the trust between company and stakeholders.

4.1.5 Waste management contractor

After the amount and type of waste is defined, the next step is to find a proper waste management contractor both for pre-treatment processes and landfilling. There should be clear plan about who will be in charge with waste collection, transportation, waste processing and eventually landfilling.

4.1.6 Off-site sorting

The off-site sorting is possible however is not recommended because contamination of clean waste due to mixed storage is highly probably. Therefore, wherever is possible on-site sorting i.e. segregation is recommended. Off-site sorting might be more sustainable when there is a strong space scarcity.

4.2 During demolition

Demolition usually starts and should be started with selective removal of materials which have sales values or had been identified as potentially harmful materials. Another option is the chemical treatment of such parts of buildings which had been contaminated during their life time. [14] Each of these operations can be treated as clearly distinguishable steps in the selective demolition process phase.

Hazardous waste needs to be removed before the actual demolition starts. Its identification is part of the planning stage, prior demolition work. The most important dangerous substances containing parts are the following:

- Mineral oil containing components
- Isolations and electrical equipment’s containing PCB
- Asbestos containing flooring
- Detectors with radioactive components

To achieve high as possible segregation rate, selective demolition and dismantling should be carried out. Proper segregation reduces transportation and other management costs.

4.2.1 Monitoring

All necessary documentation must be done in order to contribute to transparency and trust. [13] Records must be maintained on site.

4.2.2 Transportation

Demolition Waste can be very bulky; therefore, segregation practices and proximity of recycling plants is very important. [13] Finding the nearest plant and best transport network is essential to reduce environmental burdens associated with transportation emissions.

4.3 Post-demolition

4.3.1 Evaluation

After demolition, had been carried out, one should evaluate the whole process to improve both planning, segregation, transportation, choosing the waste management contractor processes.

5 Waste treatment methods

5.1 Re-use, recovery and recycling of Construction and Demolition Waste

Before any kind of recycling process, one should think about how C&D waste could be reduced. The amount of C&D waste can be reduced in many ways. Using life-cycle approach, opportunities to reduce the amount of waste and environmental impacts can be easily identified. Life cycle thinking also helps finding the best solution and supports decision making to achieve a sustainable waste management. The first step all the time should be the source reduction. This step will diminish material and energy use, furthermore prevents waste from being generated.

Other benefits associated with source reduction are:

- fewer disposal facilities
- conservation of landfill spaces
- reduction of associated environmental issues, such as air pollutant emissions, extraction of virgin sources
- reduction of the life-cycle material cost
- onsite reuse reduces transportation costs

Prior starting a recovery or recycling process the hazardousness of the raw waste must be assessed. If the waste is free of hazardous materials or the hazardous fraction can be easily located and eliminated, then the recovery process can be started. Materials recovery from Demolition Waste stream involves the sorting and separation of useful fractions from the waste. [15]

5.2 Recovery of combustible Demolition Waste fraction

There are couple of recovery techniques that can be considered in the DW management. The first and most environmentally friendly option is the re-use of construction elements, followed by material recycling, and based on the EU waste directive hierarchy the last choice should be the energy recovery. However, as we will see there might be some derogations from this hierarchy, when through Life-Cycle Assessment analysis it can be proved that any of the subordinate options would bring more environmental benefits than some superior.

5.2.1 Re-use of wood waste generated from end-of-life products

When a building element is re-used, we generally refer to its recovery as it is, or with some minor remanufacturing, having the same grade and function like before its recovery. [16] The re-use of products usually brings the highest environmental benefits, both because of avoided pollution associated with its management as a waste and energy and raw material savings due to avoided extraction and production processes.

The possibility of reusing wood waste arising from demolished buildings is highly dependent on proper deconstruction planning and its implementation. Reusing wood based structural elements is possible, and can be also economically feasible. The profitability of it can be increased by the reusability in mind already during the construction planning phase. In Finland, guidelines for designing for deconstruction have been already published, recommending that components with dissimilar service life are separated in a way that they can be easily removed separately. [16] However, re-use of timber materials is hindered by quality requirements set for construction materials [9], and CE labelling requirements. CE labelling allows traceability of the construction products and attests that their characteristics are declared as it is required. CE marking of material constructions it is mandatory since 2013.

Recovered wood is perceived as a lower quality and dirty as compared to virgin wood. It is also much easier for constructors to use standard sized new products than odd sized and processing requiring recycled timber products. In lack of market for recycled wood elements, proper regulations and legislations that would facilitate the re-use of demolition materials, the selective demolition is unsustainable.

To foster the re-use of wooden materials, timber elements should be removed selectively and sometimes even manually. Therefore, this type of demolition is perceived as costlier than the conventional one. During timber i.e. engineered wood recovery, the manual labor is even more emphasized than in the case of steel or concrete elements. [16]
Re-use of timber materials is only feasible and should be considered, if it has environmental benefits (creates less pollution, CO_2 emissions, and other environmental burdens compared to other waste management options like recycling or energy recovery processes). Another aspect that should be considered is the demand for recycled materials for re-use.

5.2.2 Recycling of wood waste generated from end-of-life products

Wood is one of the major constituent of C&D waste and there are several waste management options for it, such like re-use, recycling, combustion with energy recovery, and the last desirable being the landfilling. Its reusability and market value is varying per its origin, type, quality, and age. The challenge does not lie just in recycling but also in finding demand for the recycled wood.

Quality based classification define waste wood as Grade A, B, C, D, where Grade A stands for high quality and clean wood waste and all the others contain different and increasing number of contaminants. High quality i.e. Grade A type wood waste can be achieved by in situ segregation or by thoroughly processing the waste stream after it has been collected. To achieve a good segregation practice, the process needs to be also financially viable.

Large part of wood waste coming from demolition sites is contaminated with hazardous substances (chemical agents which are used to extend the service life time of timber products [17]), gypsum wall board, metals, plastics or concrete. Therefore, its direct re-use is not feasible neither environmentally friendly. While plasterboard is highly recyclable, it represents the major hindering factor in recycling of wood originating from demolition works.

Its level of contamination with different surface coating like paints or preservatives, makes the demolition wood waste stream difficult or even impossible to be recycled in other way than energy recovery. Untreated timber and organolhalogen free timber is suitable for recycling but organolhalohen containing and preservative treated timber qualify just for energy recovery in specialized power plants. [15]
Three trace elements: Cr, Cu, As are the main component associated with the so called CCA preservative.

Table 2. Contamination limits for recycled wood use

Elements	Limit values for recycled wood (mg/kg)
Arsenic	25
Cadmium	50
Chromium	25
Copper	40
Lead	90
Mercury	25
Fluorine	100
Chlorine	1000
Pentachlorophenol	5
Creosote	0.5

A study made by Myllymaa and Dahlbo [18] identified in Finland only a few processes that use recycled wood such like particle board production (e.g. MDF or fibreboards), material for compost, plastic composite material or manure. The rate of use of recycled wood is quite low due to its low value and due to competition with other waste sources that represent much less contamination. [19]

The use of C&D wood waste in particle board production seems to have little climate change or environmental benefits, since these boards are made out anyway from waste wood side products resulting from other wood processing industries, therefore no processes or use of virgin materials are avoided [18] Myllymaa and Dahlbo state that, by recycling demolition waste wood, carbon is “tied in long term storage” therefore, for short term the climate impacts are reduced. However, recycling of demolition wood is a downcycling solution i.e. the new products are less valuable than the old ones which have been used as raw materials. [18]
Another very important virgin wood user is the paper industry, but despite this pulp industry avoids using recycled wood, primarily because of purity requirements, i.e. contamination by non-biomass materials. [20]

However, wood waste is heavily used in energy recovery processes. Justification for this practice among others, mainly financial, has been the promotion of renewable energy sources and reduction of fossil fuels. [18]

The wood section of demolition wood waste is recycled in a very simple, efficient, and well known process, and its steps can be seen in Figure 4. First, the materials are sorted, preferably already at the demolition site, after which the wood waste is transported to the processing facility where it is shredded and after that magnetic separation the ferrous metal parts are removed. Depending on the choice of its end use, after the primary shredding the wood particles size is further reduced in a hammer mill or it is used as it is.

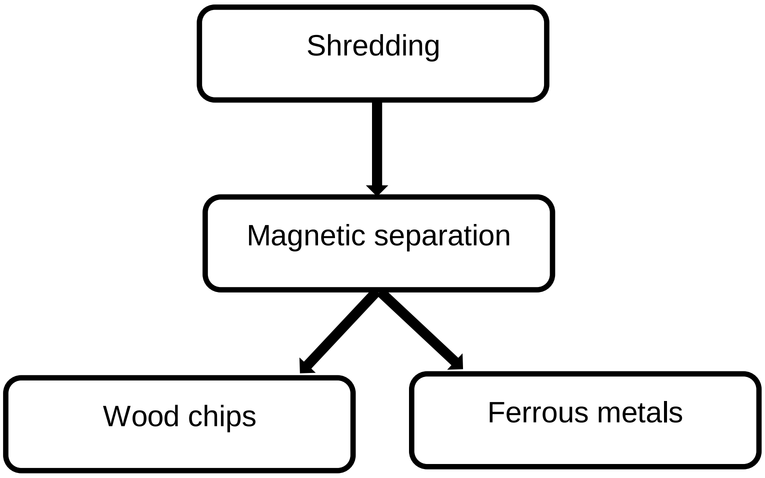


Figure 7. Recycling pathway of wood waste arising at construction sites

Other recycling outlets than energy recovery are panel board manufacturing, animal bedding or other agricultural and horticultural fields. The main barrier to use C&D wood waste for other recycling or re-use processes than energy recovery is the uncertainty of the type and grade of the wood. [21]

5.2.3 Plastics recycling

Plastics used in construction industry are classifiable in two categories: packaging and durables, the latter being the type which is generated during demolition. [22] Plastic is another Demolition Waste fraction that can be used for thermal power or electricity production through energy recovery processes. However, plastics are generally part of a mixed waste, and commonly by plastics we refer to some quite different plastic types such like polypropylene (PP), polyurethane (PU), polystyrene (PS), polyethylene (PE), polyvinyl chloride, which complicates the recycling or energy recovery processes.

Polyvinyl chloride (PVC) is a widely used synthetic plastic polymer in construction for windows or doors frame, flooring and pipes. PVC can be recycled up to six to seven times, which if we consider the lifetime of PVC products (up to 100) years, would mean a lifespan of about 600 years. Though the cost of recycled material is approximately the same as in the case of virgin materials, there is clear environmental benefit owing to avoided prime material extraction. [22] However, its energy recovery is difficult due to the high Chlorine content, which upon combustion produces HCl and can be source for dioxins in the flue gas.

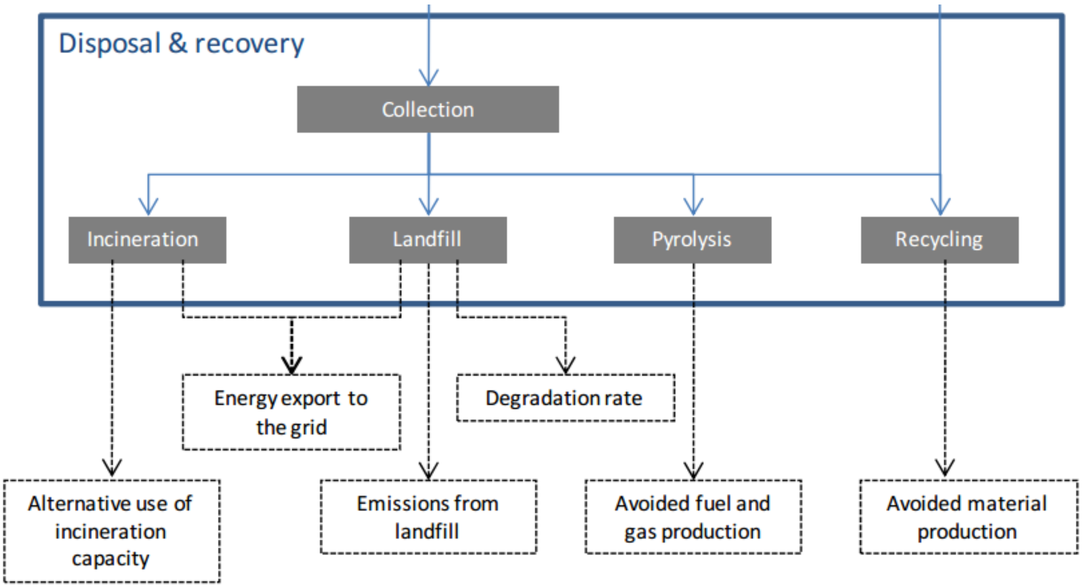


Figure 8. Plastic waste management options [23]

5.3 Recovery of non-combustible Demolition Waste fraction

5.3.1 Metals recycling

Perhaps metal is the most economically promising waste stream that can be recycled from demolition sites. The price per tonne that re-processors pay for it combined with the cost of avoided landfill taxes represents a very motivating factor for recycling process.

Based on reports and studies, in Finland the metal recovery rate is very good and there are no significate improvement possibilities.

5.3.2 Concrete and bricks recycling

Brick, concrete and masonry can be recycled on site as fill, subbase material or driveway bedding. Concrete reprocessing relies on a comparatively uncomplicated and technically mature crushing. Where landfill taxes are in force and they are based on weight, there are strong driving forces to avoid as much as possible heavy waste disposal. The first step towards this goal is recovery of these heavy components of C&D waste stream. Crushed concrete and brick can be re-used in all-weather applications (such as low-grade roads) and pavement sub-bases (roads and non-structural applications) as a substitute for virgin crushed rock.

6 Contamination of C&DW

6.1 Asbestos

Asbestos had been banned from being used in construction materials because it has been proved to be a dangerous carcinogenic material. Very strict measures must be undertaken in demolition of buildings built before its ban from construction materials. Asbestos containing materials disposal falls under hazardous waste management regulations.

In order to prevent contamination of other materials with asbestos, a thorough examination of asbestos contaminated materials has to be carried out. [24] If there is evidence of asbestos contamination, before the actual demolition, contaminated materials must be removed.

6.2 Chlorine content

The presence of Chlorine (Cl) is unwanted in combustion processes, because of its corrosion and fouling potential in boilers, and its fostering nature in PCDD and PCDF formation.

6.3 CCA

Since wood is sensitive to parasite attacks and environmental effects there was an effort to confer to it a longer service time. This has been achieved by impregnating the wood with preservative. The most common such chemical is the CCA, which is considered as a harmful chemical mostly due to its Arsenic content. Nowadays, CCA treated waste wood is treated as hazardous waste and its disposal at landfill sites has been forbidden, and since 2006 the use of CCA as wood preservative is prohibited in the EU. [25]

Due to the landfill ban, incineration of CCA treated wood gain some interest however, owing to its high concentration of heavy metals and above all its Arsenic content, the flue gas arising from CCA treated waste wood incineration facilities needs special treatment. The issue with Arsenic it is that during combustion forms oxides which can escape the incineration plants particulate filtering system, and destroy catalysts in the selective catalytic reduction equipment. [25]

7 Energy content of Demolition Waste

It would be very difficult to define by a single value the calorific value of demolition waste, since this waste stream, such like in the case of Municipal Waste, is a complex combination of materials having different energy content. Literature gives an average value of 9.8 MJ/kg LHV for untreated DW. As we mentioned already earlier, the quality of DW is a key factor not just when the goal is the material recycling but also in the case of energy recovery processes. As the purity of waste increases and the moisture content of it decreasing, the calorific value of DW is higher and higher. The best ways to increase the energy density of DW is the appropriate segregation followed by pre-treatment of the waste stream. Through increased energy content per volume, the transportation cost and transportation related environmental burdens can be significantly reduced. This is very important when distance between demolition site and nearest energy recovery facility is big. In such situations, segregation and pre-treatment of generated waste is recommended to be carried out on-site with the use of mobile waste shredders and selectors. This mobile DW shredding technology helps in situations where transportation is a sensitive issue.

Through pre-treatment of DW a much higher energy per volume bearing so called Refuse-Derived Fuel (RDF) or Solid Recovered Fuel (SRF) can be obtained. Although there is no clear regulation about energy content of these fuels, generally SRF has a 15 to 20 MJ/kg Net Calorific Value.
This value is much lower than for mainly wood comprising DW.

8 Energy recovery alternatives

A considerable part of the Demolition Waste which is not suitable for re-use or recycling processes to produce new products, can be subject of so called energy recovery processes. These processes are based on thermochemical treatments, namely incineration with energy recovery and gasification.
The above-mentioned thermochemical conversion processes differ in many aspects such us: process conditions and steps, and each of the alternatives produces different useful and waste products. Through these waste management methods, the amount of combustible waste fraction can be reduced considerably and allows significant energy recovery. [26]

The EU Waste Management Protocol defines the following materials as possible energy recovery fuels [13]:

- Contaminated wood-products which are not suitable for recycling
- Plastics
- Organic insulation materials
- Bitumen based membranes

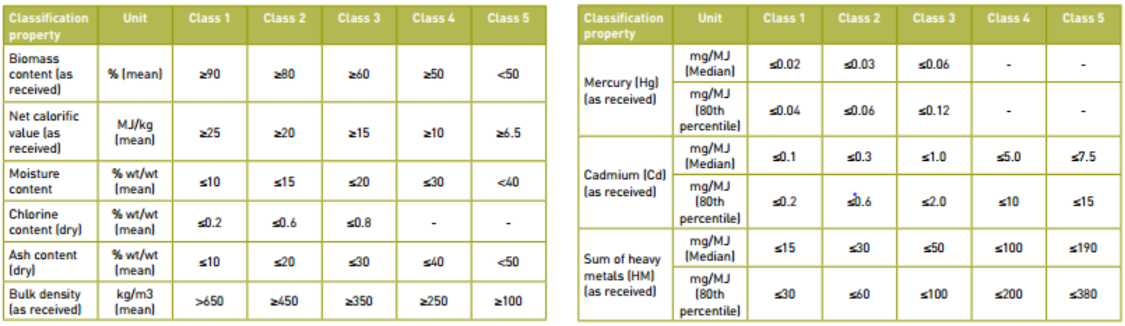
8.1 Thermal treatment of Demolition Waste

Thermal treatment with energy recovery of C&DW is considered one of the waste treatment methods. In this thesis, the focus is on thermochemical treatment of wood and plastic waste streams with energy recovery, especially in WtE plant and gasification CHP plants. Both combustion and gasification technologies are thermochemical

Studies suggest that combustible fraction of Demolition Waste can be up to 10 to 15 % of the whole C&D waste that has been generated. The main components of this combustible waste fraction are: wood, plastics, paper, and rubber. The last 20 years have seen an increasing rate of waste combustion with energy recovery. Therefore, the waste has changed its status and nowadays it is considered a fuel. This is the reason why the waste treatment industry has defined a new name for this type of fuel, namely Solid Recovered Fuel (SRF), and the European Standard (EN 15359) outline some specifications for its quality requirement.

The quality of SRF depends on certain factors such like NCV, moisture content, its hazardous material concentration, etc. Table 3. represents a short summary about the main requirements and values, the qualification of waste derived fuel is based on.

Table 3. Characterization of waste derived fuels [27]



Classification property	Unit	Class 1	Class 2	Class 3	Class 4	Class 5
Biomass content (as received)	% (mean)	≥90	≥80	≥60	≥50	<50
Net calorific value (as received)	MJ/kg (mean)	≥25	≥20	≥15	≥10	≥6.5
Moisture content	% wt/wt (mean)	≤10	≤15	≤20	≤30	<40
Chlorine content (dry)	% wt/wt (mean)	≤0.2	≤0.6	≤0.8	-	-
Ash content (dry)	% wt/wt (mean)	≤10	≤20	≤30	≤40	<50
Bulk density (as received)	kg/m3 (mean)	>650	≥450	≥350	≥250	≥100

Classification property	Unit	Class 1	Class 2	Class 3	Class 4	Class 5
Mercury (Hg) (as received)	mg/MJ (Median)	≤0.02	≤0.03	≤0.06	-	-
	mg/MJ (80th percentile)	≤0.04	≤0.06	≤0.12	-	-
Cadmium (Cd) (as received)	mg/MJ (Median)	≤0.1	≤0.3	≤1.0	≤5.0	≤7.5
	mg/MJ (80th percentile)	≤0.2	≤0.6	≤2.0	≤10	≤15
Sum of heavy metals (HM) (as received)	mg/MJ (Median)	≤15	≤30	≤50	≤100	≤190
	mg/MJ (80th percentile)	≤30	≤60	≤100	≤200	≤380

Muhammad Nasrullah states in his doctoral dissertation [28], that SRF produced from untreated C&DW was measured to have approximately 18.0 MJ/kg net calorific value (NCV) and ash content of 9.0 wt.%. The incoming, unprocessed C&DW stream was measured to have almost 10.0 MJ/kg NCV. He suggests that he quite high calorific value of C&DW, compared to other parts of Europe is due to its high wood content. [28]

8.1.1 Thermal treatment and energy recovery from demolition waste

Usually wood waste recovered from demolition sites, can be combusted without any kind of chemical pretreatment in WtE power plants however, typically requires physical removal of non-wood materials and size reduction. The extent of size reduction is determined by the boiler type in which the wood will be burned. The useful products of this thermochemical treatment in specialized power plants are electricity and heat.

Genuinely, the fuel potential of different biomasses strongly depends on their moisture content, which in the case of wood stream from demolition sites is quite low i.e. about 20%, making it a valuable fuel. Wood based fuel can have a higher heating value (HHV) up to 20 MJ/kg, however this value is highly dependent on the moisture content and the fuel particles size. Moisture content (MC) of waste wood depends on the type of wood, humidity of the environment wood is originated from, and possibly drying prior combustion. Table 5 shows a list of average calorific values of wood based fuels, based on their moisture content.

Table 4. Calorific value of wood in function of its moisture content

Moisture content (MC) of wood	Calorific value MJ/kg
0%	19.8
10%	17.8
20%	15.9
30%	14.5
40%	12
50%	10

During combined heat and power production processes, two types of wastes are generated. One of them is the bottom ash and the other is the flue-gas treatment waste. In fluidised bed boilers, the ash content of combusted Demolition Waste is 1-5 %. [29]

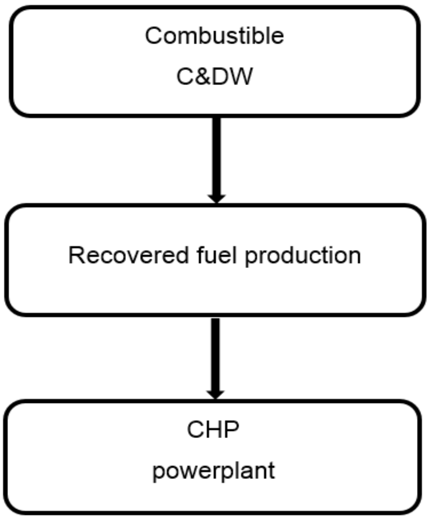


Figure 9. Energy recovery process of combustible C&D waste

Since wood coming from construction sites is considered waste, its thermal treatment is governed by The Industrial Emissions Directive (IED) 2010/75/EU [53] which is a recast of 7 (seven) previous directives including the Waste Incineration Directive 2000/76/EC (WID). This IED sets both emission limit values and monitoring requirements furthermore, defines concepts such us pollution, biomass, fuel, combustion plant, etc. If the wood waste is free of contamination it can be considered biomass and it can be burnt in facilities which are no compliant with IED requirements. [53] Generally wood originating from demolition has its surface treated (contains paint, varnish or preservatives), therefore in energy recovery processes must be thermally treated in WID compliant power plants or wood waste gasifiers.

Combustion of wood is considered carbon neutral what's more produces negative CO_2 emission because of the displacement of fossil fuels from energy production. [30]

The main environmental impacts are lower when waste wood is used in energy recovery processes however, they are heavily dependent on what extent the heat (which otherwise is just a by-product of the electricity production) is used as energy source for district heating or other industrial processes. In case of Finland, due to significant need of thermal energy for space heating, energy recovery of wood waste emerging from demolition sites, tends to be the most environmentally friendly and economically feasible material recovery solution. [9]

8.1.1.1 Emissions limit values resulting from combustion of DW

Table 5 represents average emission values the waste incineration plants must comply with. NO_x emissions vary in function of catalytic or non-catalytic reduction type.

Table 5. Emission limits from combustion

Pollutants	Mg/m3
CO	17,5
NO_x	70-100
PM	1
SO_2	10
VOC	17,5
Ammonia	3,5
Opacity	
HCL	3,5

CO_2 emissions from wood firing power plants are usually not considered in climate change calculations because of the relatively quick cycling of carbon.
“The critical element in minimizing air emissions, especially air toxics, is the elimination of CCA- and penta-treated wood from the fuel and minimizing C&D fines.” [31]

8.2 Gasification of combustible DW

The restricted oxygen availability during combustion is called gasification. By gasification embodied energy in carbon-based material is transformed into other forms of energy without actual combustion of the fuel. This results in formation of syngas or synthetic gas, containing mainly CO, water and H2. As main by-product, we should mention the smoke. Gasification has the advantage over combustion, of both better process control and less particulate emissions. The outstanding feature of gasification is the possibility of cleaning the syngas before its combustion. In this way contaminants, do not end up in flue gas thereby the energy conversion through gasification of waste and syngas burning, does not require as complicated emission control systems as waste incineration plants do. Furthermore, formation of dioxins and furans which need sufficient oxygen is impeded, since the oxygen scarce process in the gasifier does not provide the proper conditions required for their formation or reformation.

Generally, the incoming raw material requires some pre-treatment with prime goal to remove the inorganic materials such like metals, glass. Figure 9. represents a simplified gasification process flow-chart. The incoming fuel has a kind of flexibility however, it has quite strict requirements regarding its quality. This can be viewed as a drawback compared with energy recovery of wastes at WtE power plants.

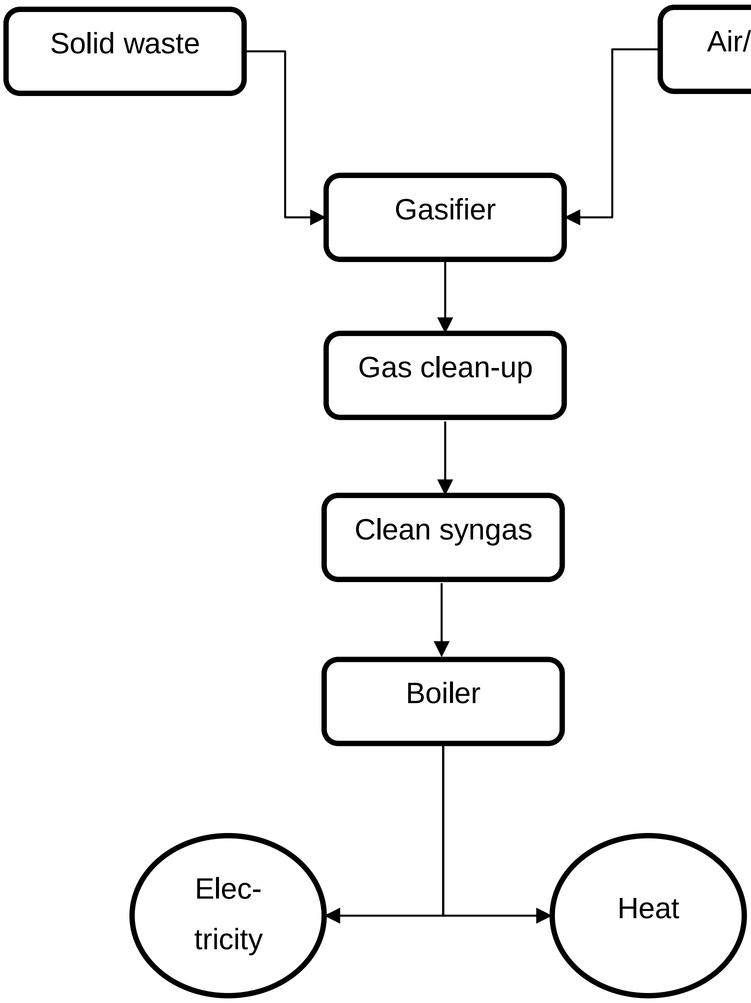


Figure 10. Simplified flowchart of gasification process

8.2.1 Kymijärvi SRF gas-fired power plant

The world first waste gasification plant had been built in 2012 in Lahti (Finland). A simplified representation of the Kymijärvi II gasification plant can be seen in Figure 11. The figure rather seeks to represent the main parts and process steps of the gasification than to be technical layout plan. The plant has a 160 MW total fuel power, having 50 MW electricity and 90 MW district heat capacity. This means that the maximum efficiency of the plant is 87.5%. The gasification takes place in two parallel 80 MW CFB gasifiers at approximately 850 °C. The heat required for the gasification process, which has more than 95% carbon conversion efficiency, is obtained by burning some of the SRF. [32]

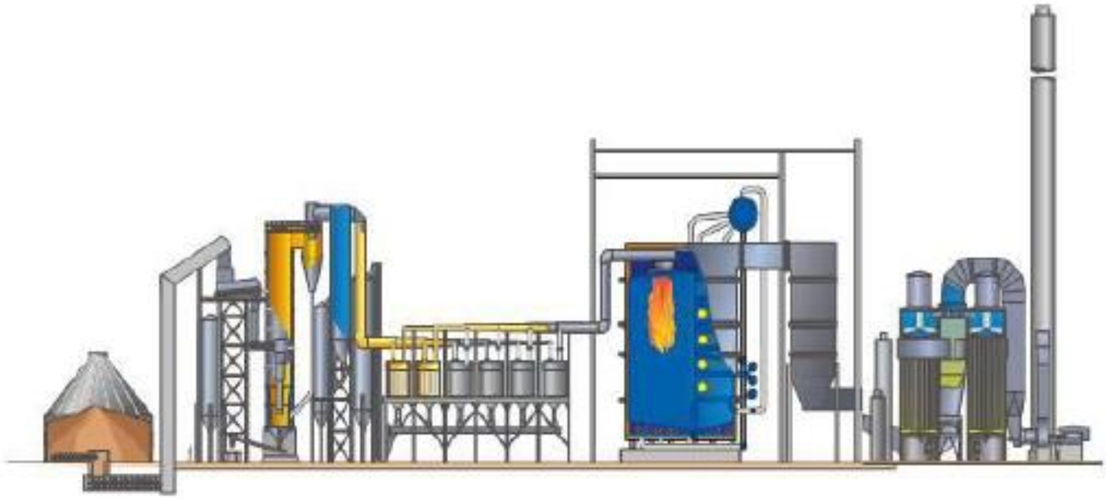


Figure 11. Kymijärvi II gasification and gas boiler plan [32]

Table 6 shows values of two flue gas measurements taken in two different day. The values show constancy in process conditions. These are the values which have been used to calculate the environmental burdens caused by the gasification process.

Table 6. Emission values measured at Kymäjärvi II plant [32]

Emission tests	**Guarantee**	**Test 1**	**Test 2**
Test conditions		**Oct. 23, 2012**	**Oct. 24, 2012**
Steam capacity (kg/s)		51.7 kg/s	46.3
O2 (%, dry)		3.8	3.7
H2O (%)		17.5	17.5
Emissions	red to 11% O2		
Dust mg/m3n, dry	10	< 2	<2
NOx (mg//m3n, dry as NO2)	200	156	155
ppm, as measured, dry		132	131
SO2 (mg/m3n, dry)	50	37	36
ppm, as measured, dry		22	21
CO (mg/m3n, dry)	100	< 2	< 2
ppm as measured, dry		< 2	< 2
HCl(mg/m3n, dry)	10	1	1
ppm as measured, dry		1	1
TOC(mg/m3n, dry)	10	< 2	< 3
Hg(mg/m3n)	0.05	< 0.05	< 0.05
Cd+Ti (mg/m3n)	0.05	< 0.05	< 0.05
Sb+As+Co+Cr+Cu+Mn+Ni+ Pb+V(mg/m3n)	0.5	< 0.5	< 0.5
Dioxins and Furans (PCDD/F) total (ng/m3n)	0.1	< 0.1	< 0.1

9 Life-cycle Assessment (LCA)

LCA is an evaluation process through which the environmental performance and burdens associated with a product or process can be analysed. Furthermore, LCA can be used as a tool to achieve sustainable development and support decision-making. LCA and life cycle thinking are widely utilised by institutions in modern environmental policy makings, and by companies to optimise their raw material consumption, waste generation and emission control. LCA enables quantification of impacts and trade-offs between different waste management options. [30]

LCA is an iterative process due to the strong correlation between its components. New information, and improvements in the process requires new iteration and re-evaluation of components to have a real and holistic view about its environmental impact. Generally, three distinctive however strongly interrelated components can be distinguished.

9.1 Life Cycle Inventory (LCI)

LCI is a data-based and objective process of quantifying raw material inputs, waste, and environmental releases i.e. outputs, throughout the whole lifecycle of a product or process. There are different methods to build up the inventory and one should select the most suitable one since they can produce different results. [33] This part of the LCA refers mainly to mass and energy inputs and outputs over the system boundaries.

9.2 Life Cycle Impact Assessment

This component of a LCA is meant to quantify and/or qualify the environmental loadings already identified in the previous component. Because of the tremendous amount, and distinct nature the impacts there is a need to convert i.e. to transform these flows into indicators or impact categories. Number and type of impact categories vary and depends on LCA method. Usually there are about 10 to 15 different categories such as: acidification, climate change, global impact, and regional impact.

Using the below formula, where of each element of impact categories can be calculated.

$$IS = \sum_{i} \sum_{x} CF_{x,i} \times M_{x,i}$$

Where *IS* is impact score, $CF_{x,i}$ is the characterization factor of substance *x* to compartment *I*, and $M_{x,I}$ stand for emission of *x* to compartment *i.*

9.3 Life Cycle Improvement Assessment

The final component is no other than a systematic evaluation of the opportunities, and the needs to reduce the environmental burdens. This process step identifies the possibilities to improve the raw material use, production process, consumer use (in case of a product), and eventually the final disposal and waste management.

9.4 Life cycle of buildings

Life cycle of buildings generally is much longer than in the case of other everyday products therefore, the re-use of materials from demolished buildings is a key element to lower environmental burdens caused by the production of new construction materials and elements. However, the re-use of building materials rises many so far unsolved issues. Above all, old buildings have not been design for disassembly in mind. The list of barriers is long, just to mention a few: there is a lack of regulations about the use of construction materials, deconstruction has much higher cost than traditional demolition, additional time, logistics and transportation cost, etc. [34]

9.5 Life cycle of wood used in construction

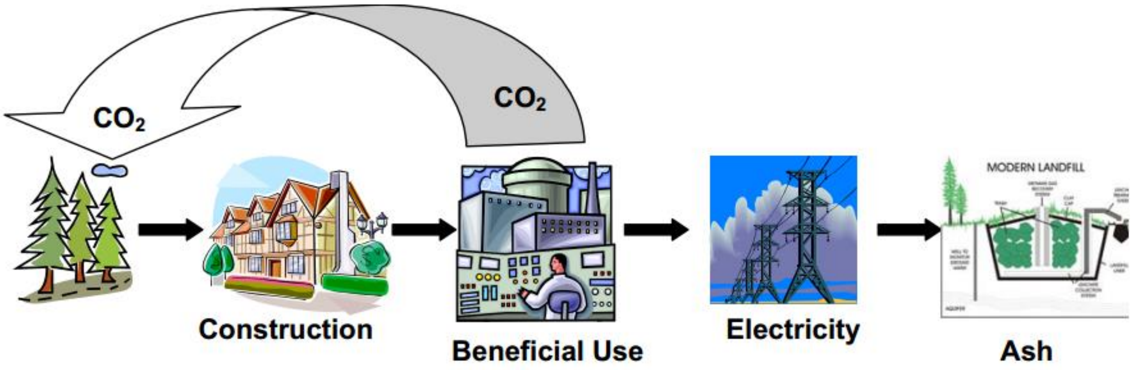


Figure 12. Life cycle of wood in construction being burnt for energy recovery purpose [30]

Jungmeier et. al. [29] define a set of distinct criteria which has to be taken into account when one is considering waste management options of wood waste. The criteria are the following:

- Quality of recovered material
- Quantity of recovered material
- Availability and state of infrastructure
- State of current and available waste management technologies, furthermore yet not mature but developing technologies
- Legislation
- Market conditions
- Costs and benefits
- Socio-economic and other factors [33]

The same paper [33] sets the main considerations in wood product LCA. The main aspects, that should be considered when waste wood is subject of energy recovery process are the technology involved and its energy efficiency, ratio of electricity and heat that can be generated by different thermochemical processes, emissions to air and eventually the bottom and fly ash treatment and disposal.

9.6 Environmental impacts related to incineration of wood

Co-utilization of waste wood in energy production contributes to reduction of emission of CO_2 into atmosphere because the amount of fossil fuel used in the power production could be reduced. However, the use of waste wood entails some environmental risks because usually timber is treated with preservatives. During combustion processes, different toxic compounds are forming which represent environmental and health risk. Overall advantages and drawbacks can be analysed by LCA.

10 LCA of energy recovery from the combustible fraction of Demolition Waste

This section describes the goal and scope of the LCA. This LCA analyses the energy recovery efficiency and environmental burdens for gasification and combustion of the combustible construction products originating from two demolition sites.

10.1 Goal and scope

The aim of this LCA was to compare two energy recovery processes of the combustible fraction of Demolition Waste, and accompanying logistics. The chosen technologies were the combustion with energy recovery in WtE power plant, and gasification followed by combustion of syngas to produce electricity and thermal energy i.e. heat. The goal was to evaluate environmental impacts, efficiency and amount of recovered energy. The simplified process steps of each technologies are listed below:

A. Incineration
  - Selective demolition
  - Material segregation
  - Transportation
  - Incineration
  - Landfilling of ash products

B. Gasification
  - Selective demolition
  - Material segregation
  - Transportation
  - Gasification
  - Syngas cleaning
  - Combustion of syngas
  - Landfilling of side products

10.1.1 Functional unit

Since the aim of the study was to assess different energy recovery methods of Demolition Waste, the function is the energy recovery and the functional unit is “energy recovery of one tonne of combustible Demolition Waste”. In the thesis two distinct energy recovery methods had been considered, namely the incineration of waste with energy recovery in the WtE power plant located in Vantaa, and waste gasification at Kymijärvi II plant in Lahti.

10.1.2 Environmental impact categories

This LCA concentrates just on the following environmental impact categories:

- global warming, in kg CO_2 equivalent
- acidification, in kg PO4 equivalent
- human toxicity, in 1,4 DCB kg equivalent

Another factor considered was the recovered embodied energy.
For the calculation of different environmental impacts the following characterization factors have been use:

10.1.3 System boundaries

System boundaries are narrow, due to limited time and data availability, and include energy input for transportation and emissions related to it, energy input for waste treatment prior to gasification, energy input for syngas clean up and the related emissions, and eventually energy output and landfilling the waste.

Exact amount of energy input for demolition work would be very difficult to estimate and it is largely dependent on the demolition method carried out. Different demolition methods have also different types and amount of emissions depending mainly at what extent demolition is mechanized or it is more manual. It was assumed that conventional and selective demolition consume approximately the same amount of energy. Both energy recovery process (incineration and gasification + incineration) need approximately the same selective demolition therefore emissions and energy inputs were set to be zero when comparing them.

A. Energy recovery through gasification

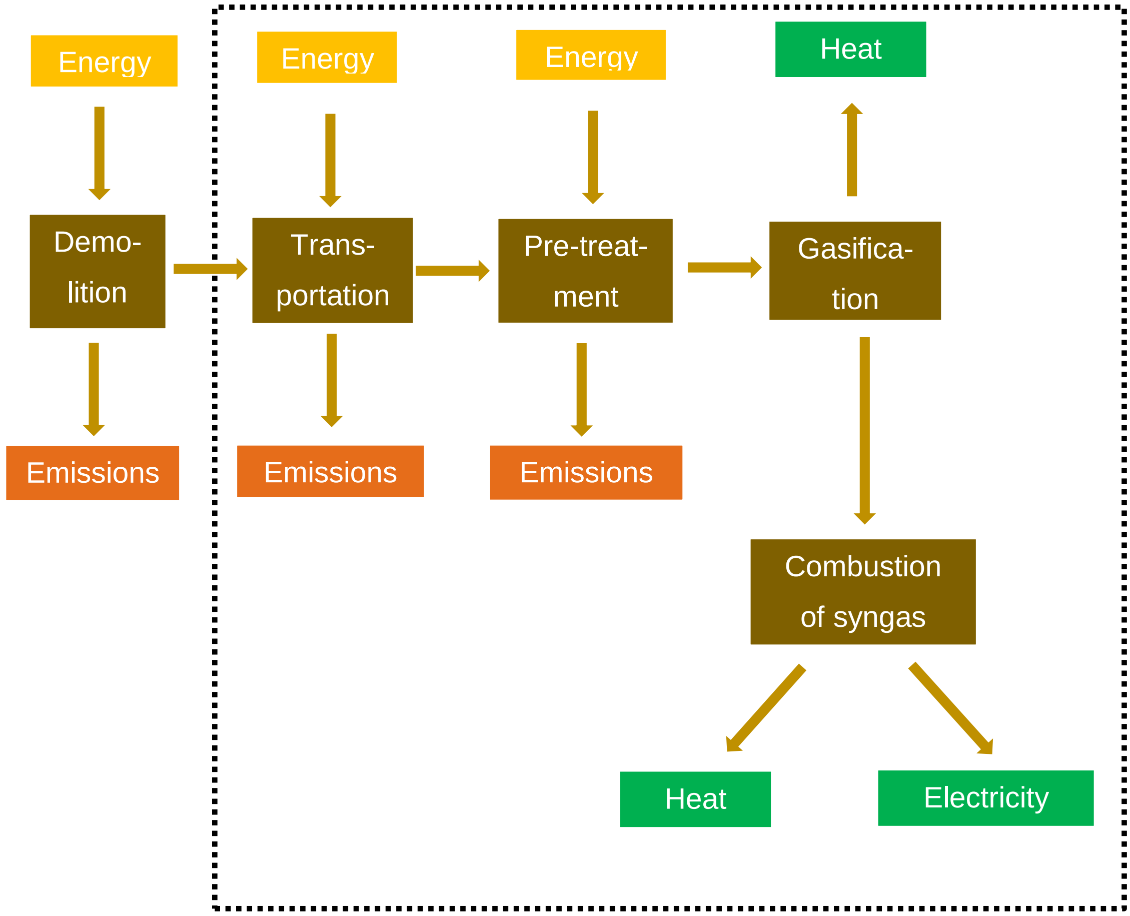


Figure 13. Process steps and system boundaries of gasification

The energy recovery from DW through combustion in WtE plant is slightly simpler than through gasification. The generated syngas is cleaned before its combustion resulting in less flue gas cleaning requirements. During energy balance calculations, it was assumed that the energy requirement for syngas cleaning after the gasification is approximately the same as the energy need for the extra flue gas cleaning in case of combustion.

B. Energy recovery through incineration in WtE power plant

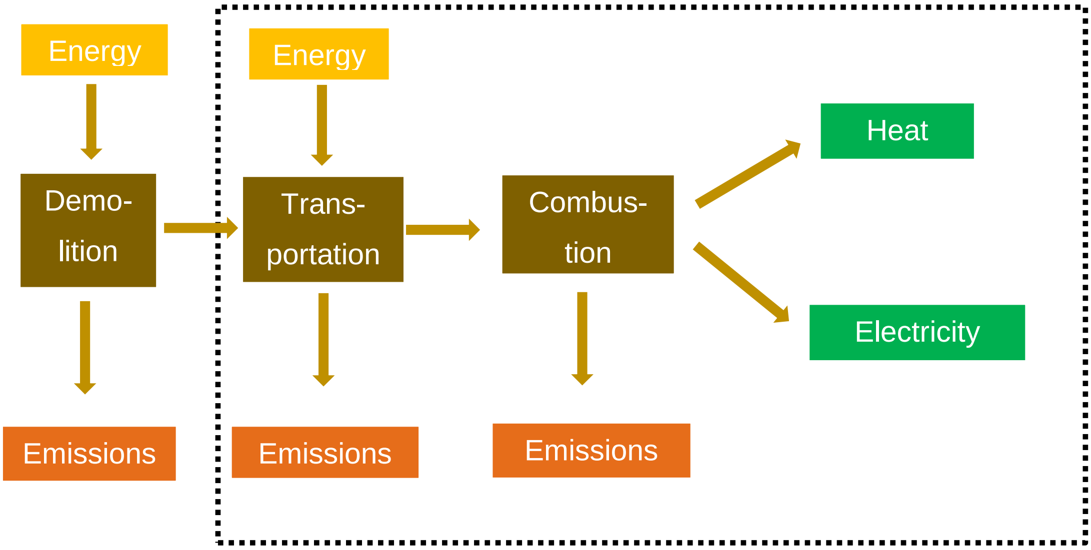


Figure 14. Process steps and system boundaries of waste incineration

10.2 Limitations and general assumptions

Several generalizations and assumptions had been made to simplify calculations and to overcome lack of data. Composition of the generated waste at our specified locations would be difficult to estimate without a thorough material analysis therefore, average values have been used throughout the calculations.

At transportation phase, it was assumed that the earth moving lorry will transport its maximum capacity. However, in real conditions this is hardly possible to be achievable therefore, the emissions and energy used by lorry's will be probably much higher than the calculated in this thesis. Situations when both electricity and heat produced during incineration and gasification of DW can be utilized, will only occur at low outside temperatures i.e. late autumn or winter. Emission values used for estimation of environmental impacts were average limitation values that must be respected due to legislations.

10.2.1 Geographical limitations

The legal framework of waste management practicalities considered is one from Finland, and transportation data are based on Finland's traffic data. Distances from demolitions sites to waste treatment facilities vary, therefore the most suitable waste management options and steps might be totally different than the analysed possibilities in this thesis.

11 Case study

11.1 Demolition sites

As case study, two different locations for DW generation have been considered, one of them is in Helsinki, and the other location is in Vantaa. The two buildings had completely different destination therefore, also the used materials are dissimilar. The one from Helsinki is an industrial building, while the Vantaa's location is a residential dwelling. Disregarding the non-combustible waste fraction two different DW types had been estimated to arise from the two locations. During calculations, it has been assumed that the DW generated at Helsinki's site is mainly mixed demolition waste, while DW originating from Vantaa's site is primarily wood waste. Based on these facts, two scenarios have been built up.

In **Scenario 1**, the analysed DW is mixed demolition waste from Helsinki, energy recovery methods are combustion with energy recovery in Vantaa's WtE plant, and gasification in Lahti's Kymijärvi II plant.
Scenario 2 wastes contains mostly wood and comes from Vantaa's site. The energy recovery processes take place in the same locations as in **Scenario 1**. Distance from the two demolition sites to the chosen energy recovery facilities is approximately the same therefore, it was assumed that when comparing same type of thermochemical treatment, the environmental burden and energy efficiency differences between **Scenario 1** and **Scenario 2** will originate principally from differences in technologies and the waste types.

11.2 Distance and transportation

For the estimation of distances, the Google Maps software has been used and route has been chosen without taking into consideration any sort of weight or height restriction that could occur. The total distance that was used for emission and energy calculations, includes both the way when waste is transported from demolition site to waste treatment facility, and the way back to the demolition site.

Distances from Helsinki’s site:

- Rorokuja → WtE Vantaa: 16 km (10 km urban, and 6 km highway)
- Rorokuja → Kymijärvi II, Lahti: 107 km (10 km urban, and 97 km highway)

Distances for Vantaa’s site:

- Orvokkirinne → WtE Vantaa: 9 km (5 km urban, and 4 km highway)
- Orvokkirinne → WtE Kymijärvi II, Lahti: 95 km (3 km urban, and 92 highway)

11.3 Results and calculations

11.3.1 Energy analysis of incineration and gasification

For the calculations of energy recovery rate, it has been supposed that there is a demand both for the electricity and heat produced during thermochemical treatment of DW. It is easy to see that the highest energy recovery can be obtained when the heat gained through combustion of waste it is supplied as district heat. [35] Therefore, the location of WtE plants is crucial in the efficient utilization of recovered thermal energy. When only electricity it is produced during combustion, the efficiency of the process usually ranges between 20-35 %.

Recovered energy i.e. the output from the gasification process was calculated separately for electricity, having a share of 31.25 % from the total energy potential stored in the waste, and for generated heat which stands for 56.25 % from the same available energy feedstock. Efficiency values used for the gasification and WtE plants were 87.5% for the former, and 95.5 % for the latter. The maximum 95.5% efficiency is a combination of the 38.5% electricity and 57% thermal energy efficiency [36].

Figure 15 shows the energy input and output analysis of gasification and combustion processes. The waste was supposed that is transported without any pre-treatment to the WTE plant located in Vantaa having 9.8 MJ/kg NCV. In the case of gasification, it was supposed that the energy upgrading to 18 MJ/kg takes place after its transportation to Lahti. The assumptions regarding NCV of DW were based on measurements done by Nasrullah, M. [28] Literature give approximately similar NCV values, being between 14-26 MJ/kg. Nasrullah [28] found that about 44% of the shredded and sorted DW has been recovered as SRF, which means that after pre-treatment of raw DW the remaining SRF mass is 440 kg, which means

0.44* 18000 MJ = 7920 MJ heating value

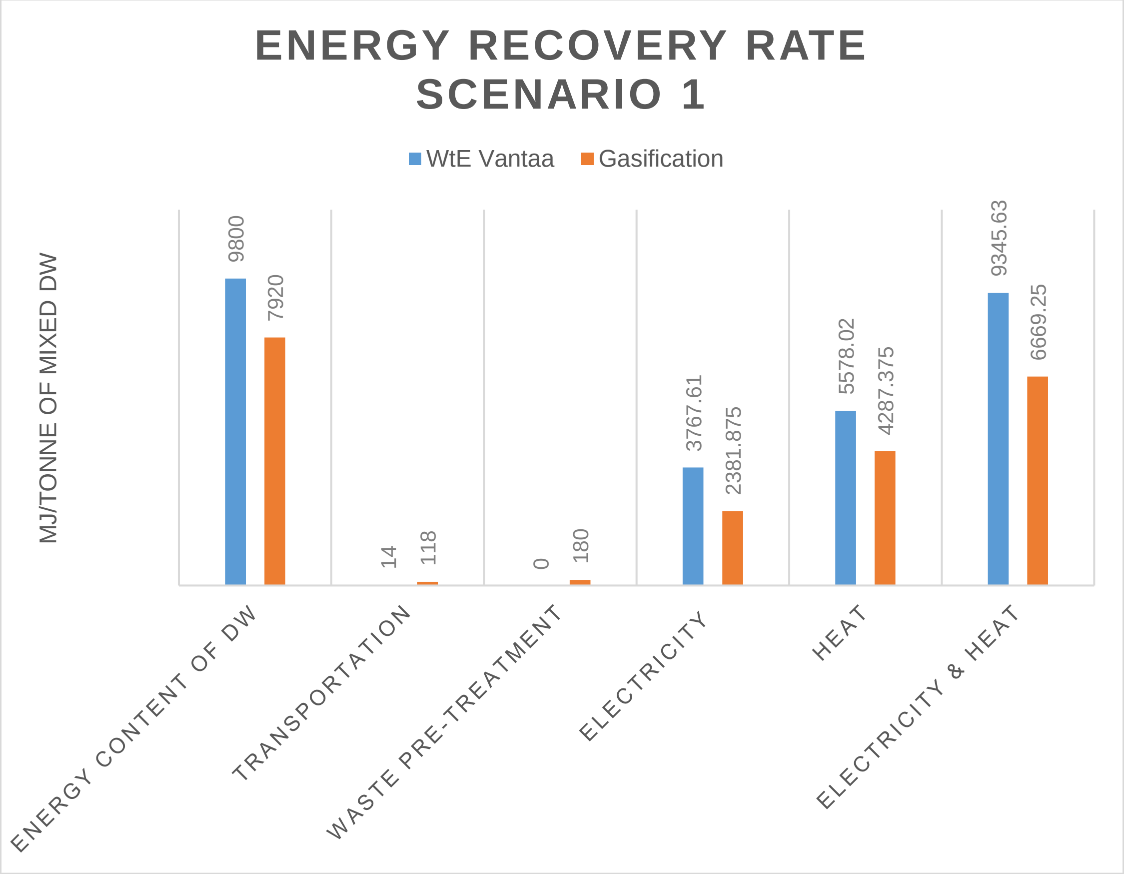


Figure 15. Energy balance for Scenario 1

In **Scenario 2**, the NCV of mainly wood containing DW was assumed to be 16.25 MJ/kg, which corresponds to an average 15-20% moisture content. The 16.25 MJ/kg NCV was obtained by calculating the flue gas volume and dividing it by the Fuel Factor, the result being the heating value of the fuel.

To calculate the flue gas volume generated during combustion of mainly wood containing demolition waste the following formula was used:

$$\mathbf{V_{God} = 8.8930\,\gamma_C + 20.9724\,\gamma_H + 3.3190\,\gamma_S - 2.6424\,\gamma_O + 0.7997\,\gamma_N} \quad [37]$$

where V_{God} is the volume of the flue gas generated by burning the fuel, γ_C is the Carbon content of the fuel (by mass), γ_H stands for Hydrogen content, γ_S represents the mass of Sulphur in the fuel, γ_O is the oxygen content of fuel, and eventually γ_N is the Nitrogen content.

The Carbon, Hydrogen, Sulphur, Nitrogen, and Oxygen content of the fuel was assumed to correspond to average mixed waste wood (see Table 7). The result obtained was

$$V_{God} = 4.78 \text{ m\^{}3/kg of fuel,}$$

which divided by the afferent 0.294 MJ/kg Fuel Factor value gives about

$$NCV = 16.25 \text{ MJ/kg of fuel.}$$

It was also assumed that pre-treatment of the waste takes place after its transportation to Lahti. Pre-treatment was assumed to cause small increase in energy density due to the reasonably clean nature of demolition wood waste. Energy balance of **Scenario 2** can be seen in Figure 16. The 16200 MJ energy input into the gasification process is the result of the assumption that about 90% of the raw wood based DW is recovered as SRF.

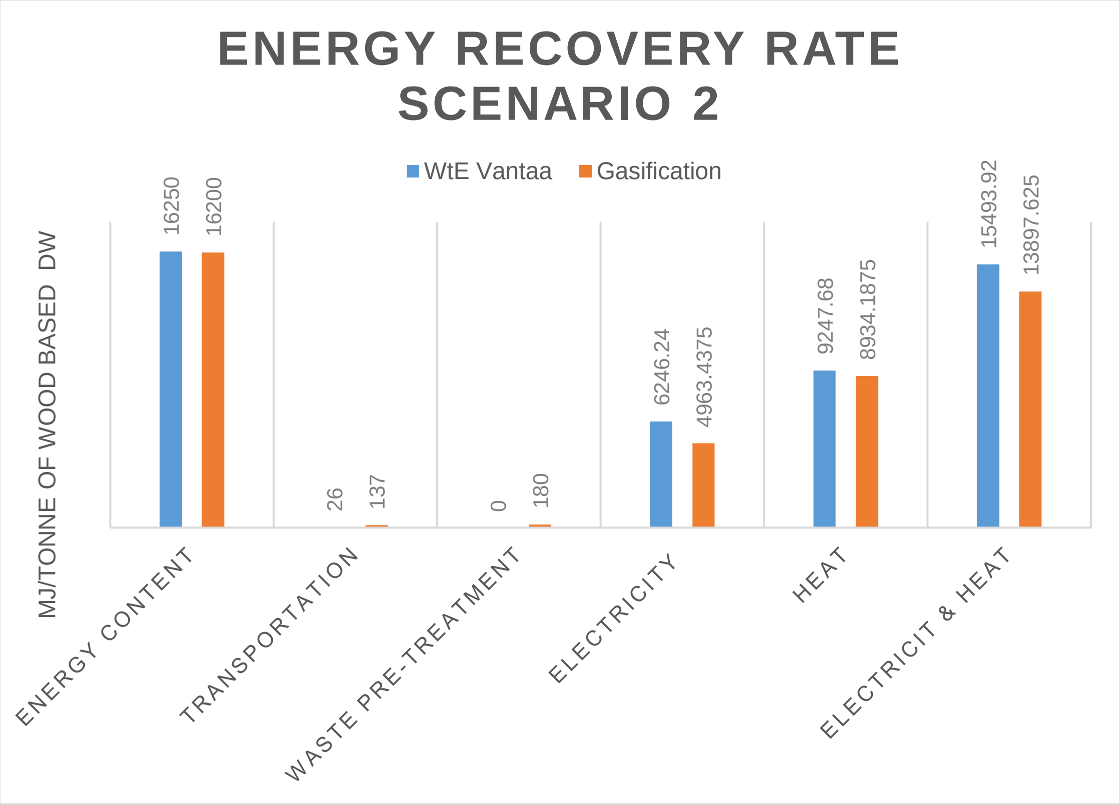


Figure 16. Energy balance for Scenario 2

11.4 Emissions from combustion and gasification processes and related logistics

Calculations of the flue gas volumes, emitted during incineration of the waste and combustion of syngas, had been carried out using average Fuel Factor conversion values and Formula 1. The reference values for Fuel Factor can be found in Table 7 and Table 8.

Table 7. Fuel factors using measured $H_{(N)}$ values [37]

Fuel type	C (w %)	H (w %)	O (w %)	N (w %)	S (w %)	Ash (w %)	V_{God} (m^3/kg)	$H_{(N)}$ (MJ/kg)	Fuel Factor$_{)}$ (m^3/MJ)
Bark average	52.30	6.00	40.00	0.20	0.00	1.60	4.85	19.19	0.253
Wood pellets	50.10	6.07	43.20	0.09	0.01	0.50	4.59	18.61	0.247
Forest residue	50.30	4.59	40.00	1.03	0.11	4.00	4.39	19.17	0.229
Waste wood	50.50	5.95	35.50	0.53	0.06	7.40	4.81	-	-
Finnish peat	54.40	5.90	35.10	1.10	0.15	4.20	5.16	23.32	0.221
Barley	46.80	5.53	41.90	0.41	0.06	4.90	4.22	17.56	0.240
Brown coal German	63.90	4.97	24.50	0.57	0.48	4.50	6.10	24.02	0.254
Mixed waste wood	50.70	5.91	40.10	1.68	0.06	1.40	4.70	16.00	0.294
Municipal solid waste	33.90	4.60	22.40	0.70	0.40	38.00	3.41	12.10	0.282
MSW plastic Netherlands	81.10	13.33	0.00	0.11	0.01	4.40	10.01	39.18	0.255

11.4.1 Flue gas volume generated by thermochemical treatment of wood based DW

A. Combustion at WtE

Fuel Factor values are 0.294 m^3/MJ in case of the mixed wood waste (Table 7), and 0.240 m^3/MJ (Table 8) for fuel in gaseous phase. After the volume of flue gas had been found, the amount of pollutants was calculated. For combustion of mostly wood waste containing DW the flue gas volume for one tonne of waste was found to be

V_{God} = 4780 m^3/tonne of wood based DW.

The values are informative and highly fuel type dependent. More exact values can be obtained by analysing a sample of as homogeneous as possible fuel.

B. Gasification at Kymijärvi

The gasification of mostly wood containing DW has been carried out in the similar way as in the case of mixed waste gasification (see Figure17). With a material recovery efficiency of 90% during SRF production, about 900 kg of SRF is generated from 1000 kg of DW. This gives as a 2700 kg mass of syngas, with 6 MJ assumed heating value. The total volume of flue gas obtained and used in emission calculations was

V_{God} = 3888 m^3/tonne of raw DW

Table 8. Average fuel factor (S) for fuels in different phase [37]

Fuel Factor **S**	**Fuel type**		
	Gas	**Liquid**	**Solid**
m^3/MJ at 0% O_2 dry 273.15K & 101.325kPa	0.240	0.244	0.256
$U_{R,95\%}$	± 0.7%	± 1.5%	± 2.0%

11.4.2 Flue gas volume generated by mixed DW thermochemical treatment

The average syngas NCV is about 5 MJ/kg [32] of syngas and the SRF produced from mixed DW has a NCV of 18 MJ/kg. Based on the assumption that the Carbon conversion during the gasification is about 97% [32] thereby, it was assumed that there is insignificant energy loss and the produced syngas contains almost the entire 18000 MJ heating value. According to Nasrullah [28], from one tonne of mixed DW about 440 kg of SRF is produced (44% recovered material), which means that from the original one tonne of DW remains 440 kg of SRF which contains 7920 MJ energy. Now, if one kilogram syngas has about 6 MJ energy, it means that about 1320 kg of syngas has been generated. By multiplying the mass of syngas with the V_{God} (see calculation in Figure17) we get the total amount of flue gas. The flow chart for flue gas calculation can be seen in Figure17.

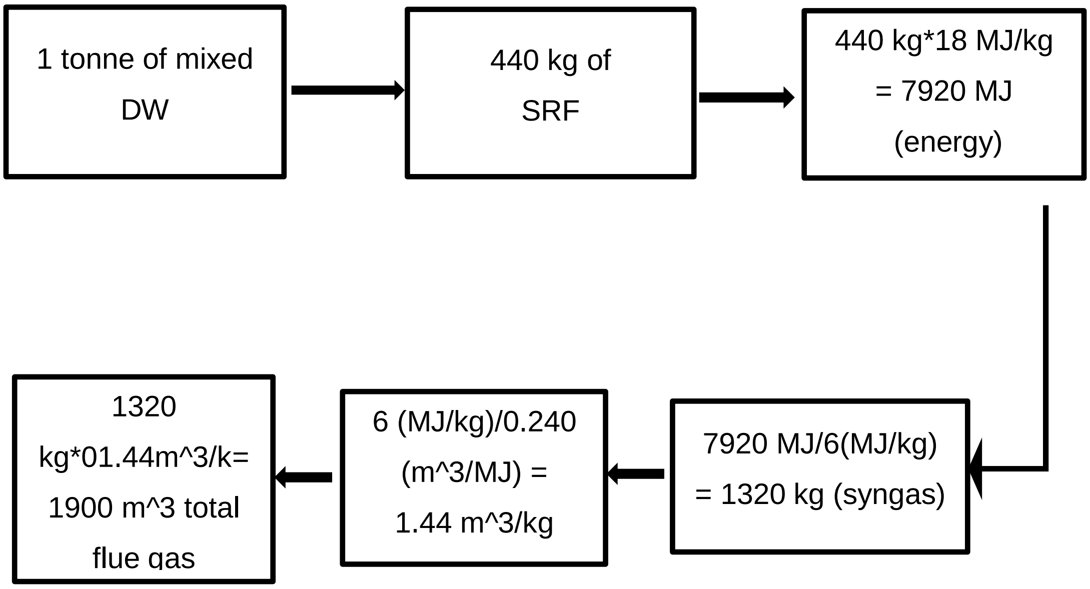


Figure 17. Flow chart of flue gas calculation

Based on this calculation the emissions and environmental impacts have been computed for

V_{God} = 1900 m^3/tonne of raw mixed DW

11.5 Environmental impacts

Three environmental impact categories had been selected, namely: Global Warming Potential (GWP), Acidification, and Human Toxicity. The pollutants that have been used to compute the impact categories are represented in Table 9.

Table 9. Impact categories and afferent pollutants

Pollutants Impact categories	CO_2	CH_4	N_2O	SO_2	NO_x	PM	NH_3
Global warming	x	x	x				
Acidification		x	x	x			
Human Toxicity				x	x	x	x

11.5.1 Global Warming

Figure 18 shows GWP for both scenarios but only for the transportation. A significant difference can be noticed when the transportation route is mainly in urban area. In this case, even for short distance, routes from the two demolition sites to Vantaa's WtE power plant, the GWP is almost doubled from 1 kg to almost 2 kg (Figure 18).

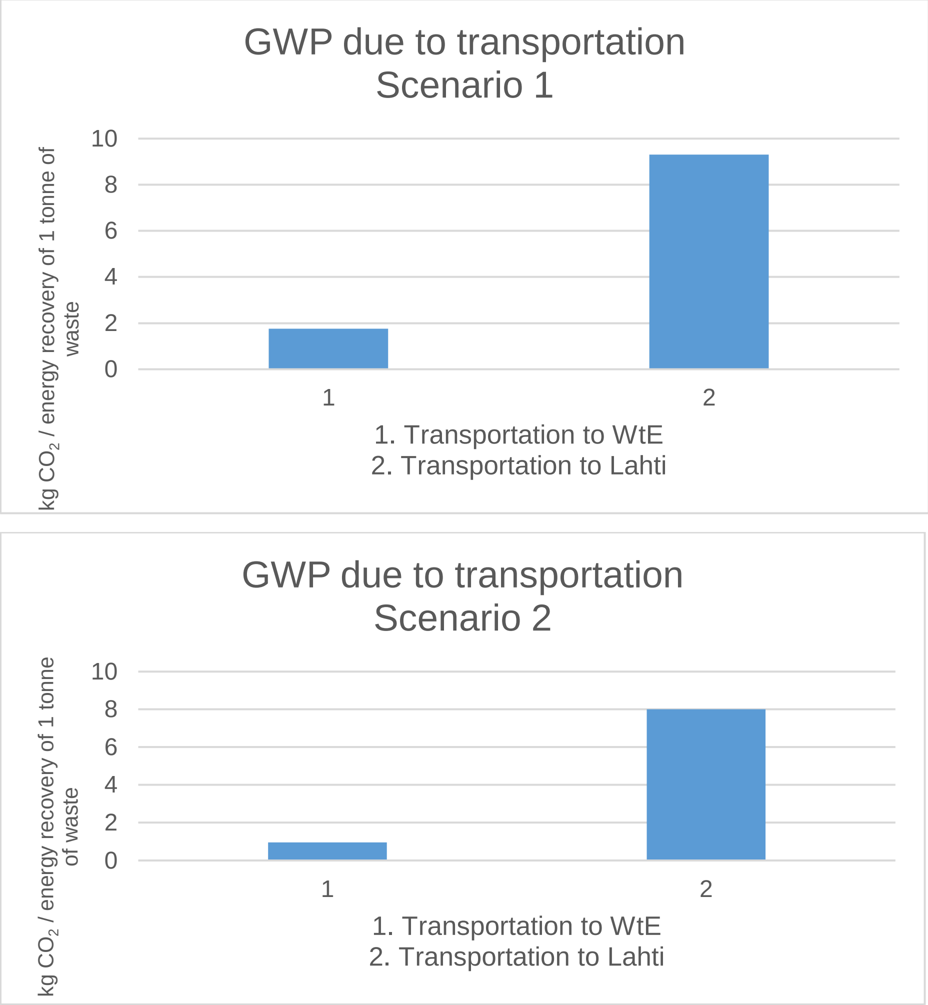


Figure 18. Global Warming Potential of transportation for Scenario 1 (Helsinki site)

The overwhelming part in GWP comes from the CO_2 emission, which in case of transportation originates from fossil fuel therefore it had been included in both scenarios. Just to emphasize the share of CO_2 from the overall GWP, its contribution to the GW impact categories it is separately shown in Table 19. CO_2 emission was split for urban and highway transportation distances as well. The small difference between GWP value and merged urban and highway CO_2 sum comes from CH_4 and N_2O emissions.

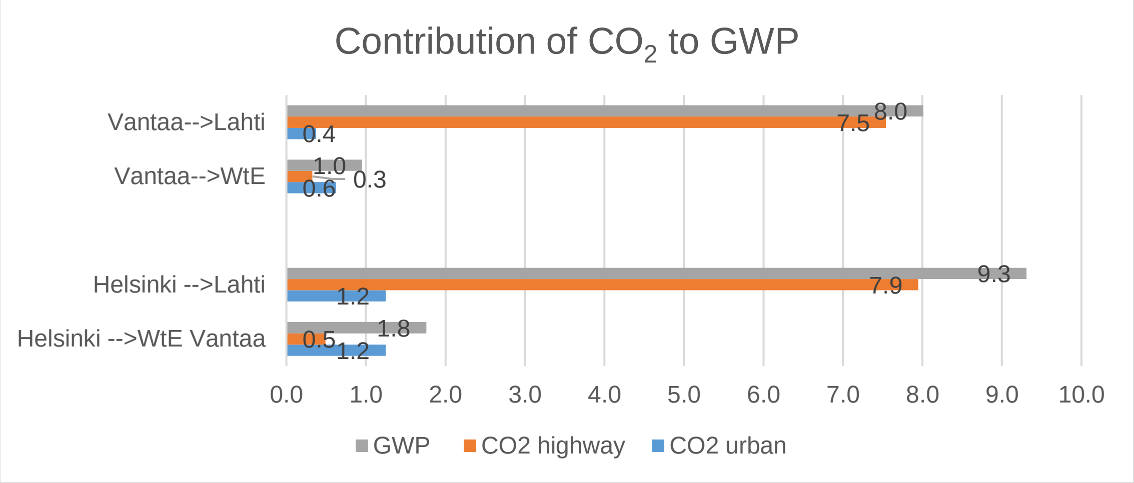


Figure 19. Contribution of CO_2 to GWP

In **Scenario 2** the CO_2 emission had been disregarded due to the nature of the fuel, which had been considered to contain mainly bio Carbon hence, the energy recovery of DW processes was assumed to be carbon neutral. The situation in **Scenario 1** is different since the waste in this case is a mixed DW, and based on the type and construction material of the building situated at Rorokuja (Helsinki), for the calculations, we assumed that mixed DW has none or just insignificant amount of bio carbon content. Another assumption was that the Carbon content of the raw mixed DW was 30 w%, and after it has been upgraded to SRF was about 53 w%. The Carbon content assumptions were based on the NCV value of the combusted (9.8 MJ/kg), respectively gasified (18 MJ/kg) DW. The CO_2 emission calculation for **Scenario 1** was carried out in the following way:

Step1: 53 w% means 530 g/1000 g of SRF
Step2: C content of CO_2 is about 27.3%
Step3: oxidation of 530 g of Carbon generates 1941 g of CO_2
Step4: 1 kg of mixed DW gives 440 g of SRF
Step5: 440 kg of SRF generates 440*1.95 kg = 854 kg of CO_2
Result: 854 kg *87.5% efficiency = **747 kg** of CO_2

Calculations for the raw mixed DW had been carried out in the similar way resulting in **1049 kg** of CO_2 for every kilogram of DW burned.

As we can see in Figure 20, when the Carbon content of the waste is not bio but has fissile origins, just as in **Scenario 1** the GWP of the energy recovery processes is huge compared to **Scenario 2.**

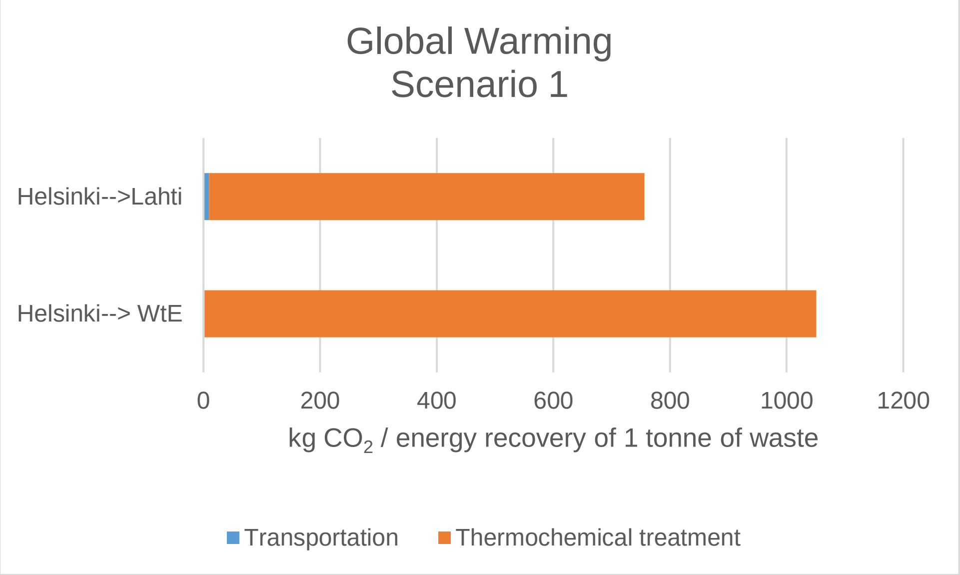
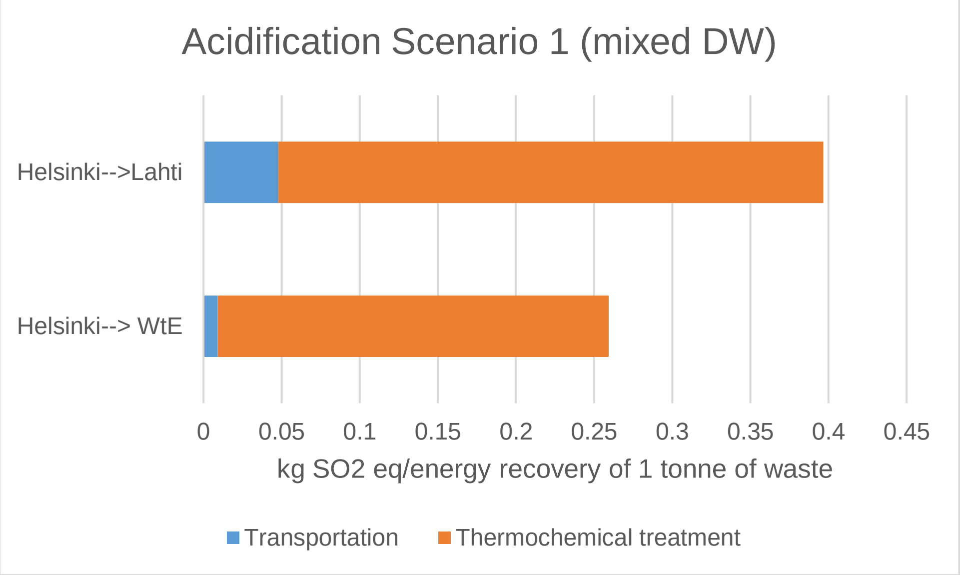


Figure 20. GWP of Scenario 1

11.5.2 Acidification

If for Global Warming Potential the transportation completely dominates, the situation is dramatically changed when we study the Acidification and Human Toxicity categories. For these categories, the thermochemical energy recovery processes generate much of the environmental burdens. The results for the Acidification can be seen in Figure 21.



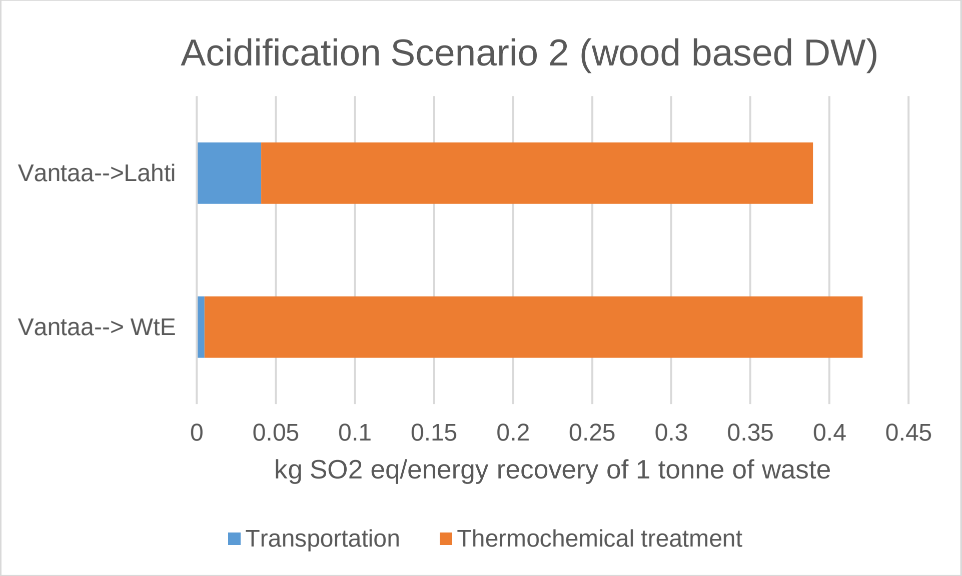
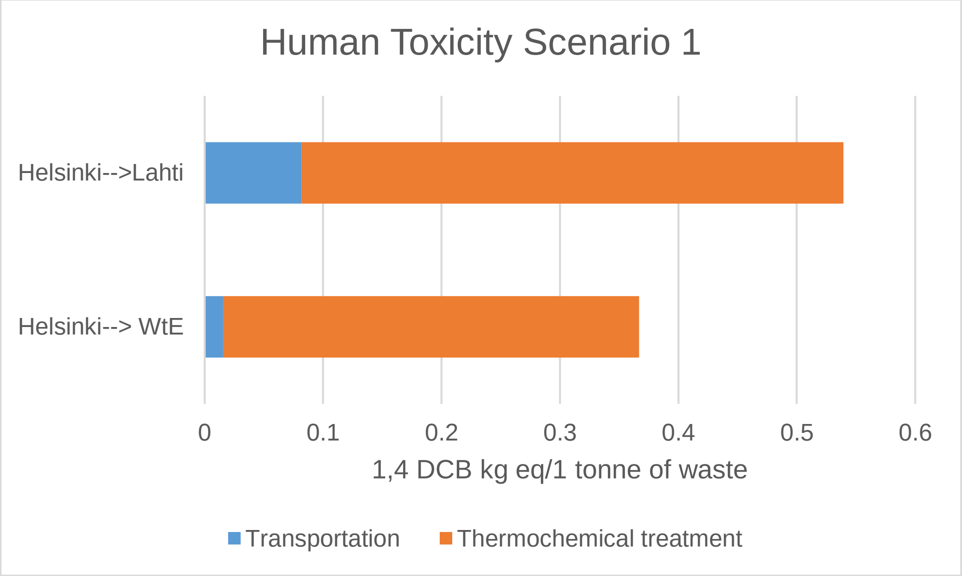


Figure 21. Combined Acidification potential of transportation and thermochemical processes

11.5.3 Human Toxicity

As we can see, combustion has larger impact both in Acidification and Human Toxicity case when the fuel is mixed waste, meanwhile when the DW contains mainly wood gasification causes less environmental burdens for these two categories. This can be explained by the higher energy density of the transported DW.

Human Toxicity values are represented and compared in Figure 22.



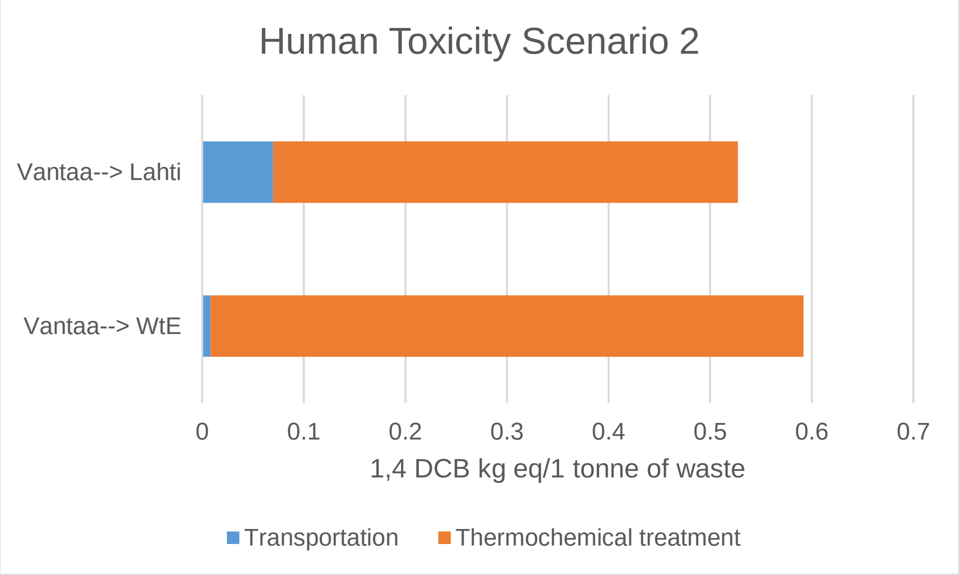


Figure 22. Human Toxicity potential arising from combined impact of transportation and thermal treatment of DW

12 Conclusion

Compared with other European countries, in Finland wood represents the largest part of the combustible and one of the most significant part of the demolition waste. This fact faces Finland with the difficulty, to be in compliance with the EU demolition waste recycling target. Due to other industrial processes, which side products is wood waste, material recycling of demolition wood waste is hindered. Generally, the quality of wood waste generated at demolition sites is lower and there is an extra cost associated with its recycling compared with other wood wastes.

Studies suggests that one of the most feasible demolition waste management is the energy recovery. However, in order to increase the energy recovery rate and in the same time to decrease the environmental burdens related to energy recovery processes a careful segregation should be carried out.

Each analysed energy recovery technique (combustion and gasification), has its advantages and drawbacks. If generated Demolition Waste is going to be incinerated with energy recovery at Vantaa’s WtE plant, the waste does not have to be pre-treated and due to the unnecessary pre-treatment, pollution related to treatment can be avoided and energy saved. In case of both analysed demolition sites the transportation distance is shorter to WtE which results in lower environmental impacts and energy efficiency. Due to the extremely high efficiency of the WtE plant, the amount of recovered energy is higher when the thermal treatment with energy recovery takes place in Vantaa's WtE plant.

Owing to the quite big distance from demolition sites to Kymijärvi II gasification plant, the treatment of DW before its transportation to Lahti bear obvious benefits due to mass and volume reduction. Nasrullah [28] found that about 44% of the shredded and sorted DW has been recovered as SRF, which means that emissions due to transportation can be halved. Literature associates a higher material recovery rate and more flexible energy management options with the gasification technology since, DW is not directly combusted but gasified, having the syngas as useful product, which can have multiple use. Syngas can be used in internal combustion engines or transformed into biofuel. Combustion with the goal of energy recovery can take place onsite or somewhere else and at some other time, when the largest amount of its energy can be utilized.

Assessment of energy recovery options needs further studies and a more reliable data base regarding quantity, quality and origin of Demolition Waste. By the help of these well documented data bases more trustworthy Life Cycle Analysis can be carried out, contributing to the decision making in the DW recycling options.

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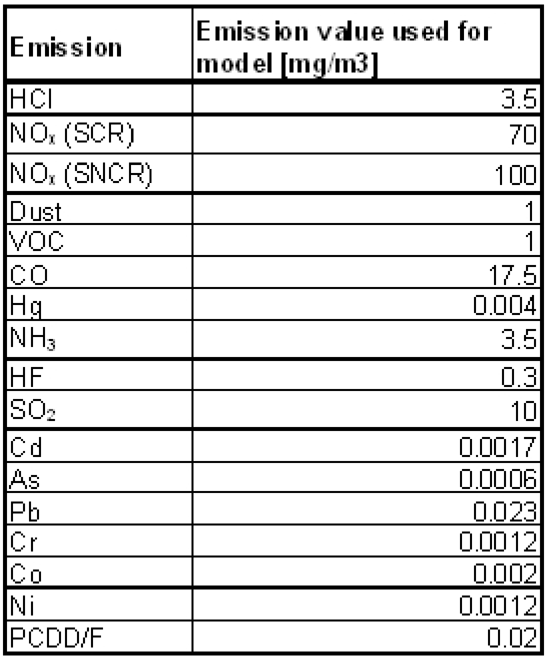
53 Directive 2010/75/EU of the European Parliament and the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control)

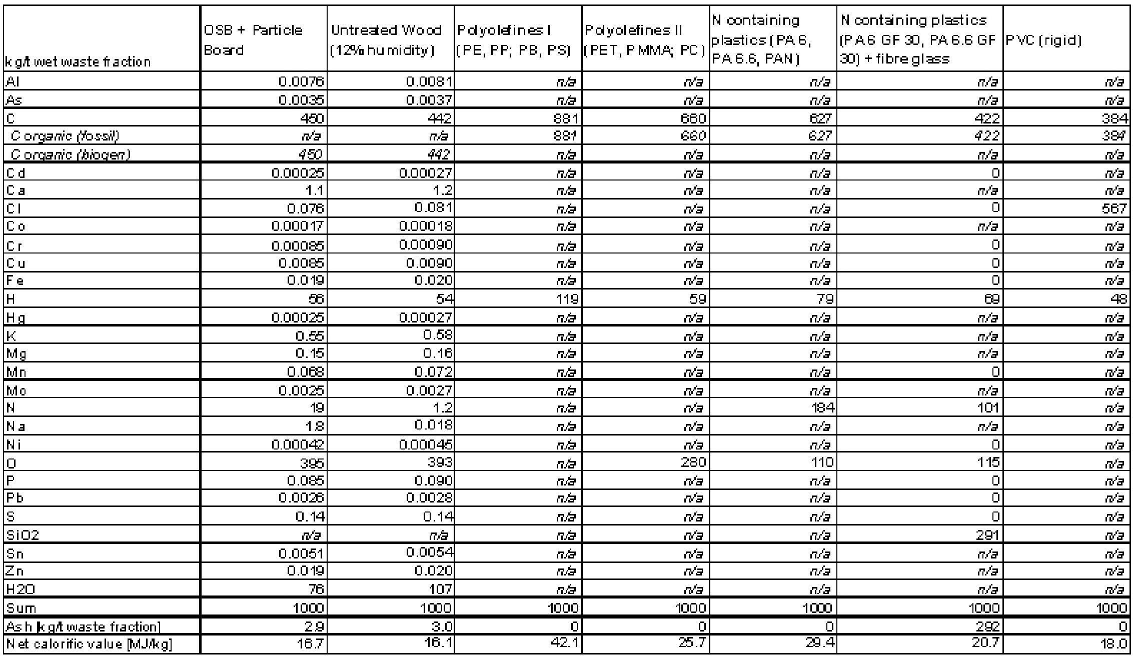
Appendix1 **Emission limits**



Emission	Emission value used for model [mg/m3]
HCl	3.5
NO_x (SCR)	70
NO_x (SNCR)	100
Dust	1
VOC	1
CO	17.5
Hg	0.004
NH_3	3.5
HF	0.3
SO_2	10
Cd	0.0017
As	0.0006
Pb	0.023
Cr	0.0012
Co	0.002
Ni	0.0012
PCDD/F	0.02

http://eplca.jrc.ec.europa.eu/ELCD3/resource/sources/c5c00110-3d47-11dd-ae16-0800200c9a66/PE_LBP-GaBi_End-of-Life_Waste_incineration_Emission_table_c5c00110-3d47-11dd-ae16-0800200c9a66.jpg

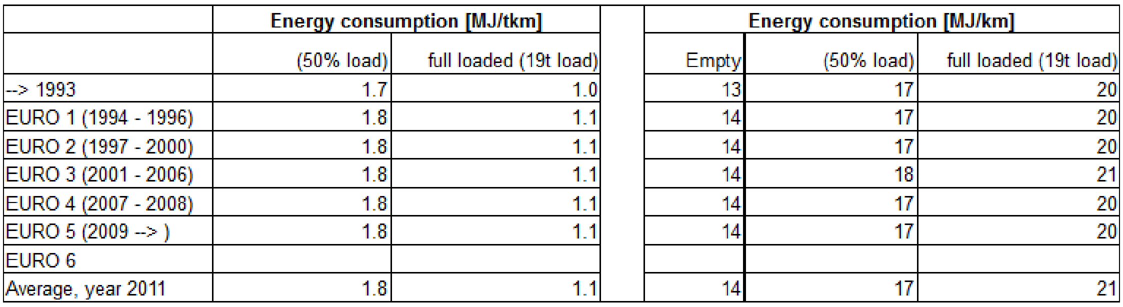
Appendix2 **Chemical composition of different materials arising at demolition sites**



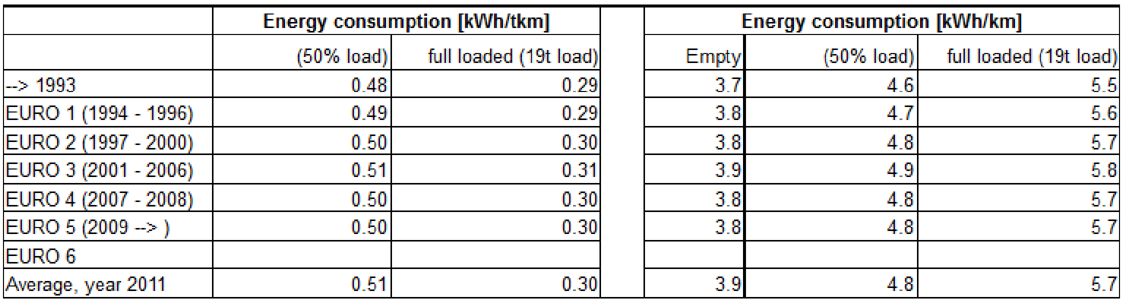
kg/t wet waste fraction	OSB + Particle Board	Untreated Wood (12% humidity)	Polyolefines I (PE, PP; PB, PS)	Polyolefines II (PET, PMMA; PC)	N containing plastics (PA 6, PA 6.6, PAN)	N containing plastics (PA 6 GF 30, PA 6.6 GF 30) + fibre glass	PVC (rigid)
Al	0.0076	0.0081	n/a	n/a	n/a	n/a	n/a
As	0.0035	0.0037	n/a	n/a	n/a	n/a	n/a
C	450	442	881	660	627	422	384
C organic (fossil)	*n/a*	*n/a*	*881*	*660*	*627*	*422*	*384*
C organic (biogen)	*450*	*442*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
Cd	0.00025	0.00027	n/a	n/a	n/a	0	n/a
Ca	1.1	1.2	n/a	n/a	n/a	n/a	n/a
Cl	0.076	0.081	n/a	n/a	n/a	0	567
Co	0.00017	0.00018	n/a	n/a	n/a	n/a	n/a
Cr	0.00085	0.00090	n/a	n/a	n/a	0	n/a
Cu	0.0085	0.0090	n/a	n/a	n/a	0	n/a
Fe	0.019	0.020	n/a	n/a	n/a	0	n/a
H	56	54	119	59	79	69	48
Hg	0.00025	0.00027	n/a	n/a	n/a	n/a	n/a
K	0.55	0.58	n/a	n/a	n/a	n/a	n/a
Mg	0.15	0.16	n/a	n/a	n/a	n/a	n/a
Mn	0.068	0.072	n/a	n/a	n/a	0	n/a
Mo	0.0025	0.0027	n/a	n/a	n/a	n/a	n/a
N	19	1.2	n/a	n/a	184	101	n/a
Na	1.8	0.018	n/a	n/a	n/a	n/a	n/a
Ni	0.00042	0.00045	n/a	n/a	n/a	0	n/a
O	395	393	n/a	280	110	115	n/a
P	0.085	0.090	n/a	n/a	n/a	0	n/a
Pb	0.0026	0.0028	n/a	n/a	n/a	0	n/a
S	0.14	0.14	n/a	n/a	n/a	0	n/a
SiO2	n/a	n/a	n/a	n/a	n/a	291	n/a
Sn	0.0051	0.0054	n/a	n/a	n/a	n/a	n/a
Zn	0.019	0.020	n/a	n/a	n/a	n/a	n/a
H2O	76	107	n/a	n/a	n/a	n/a	n/a
Sum	1000	1000	1000	1000	1000	1000	1000
Ash [kg/t waste fraction]	2.9	3.0	0	0	0	292	0
Net calorific value [MJ/kg]	16.7	16.1	42.1	25.7	29.4	20.7	18.0

http://eplca.jrc.ec.europa.eu/ELCD3/resource/sources/16e9b2c5-3c44-11dd-ae16-0800200c9a66/PE_LBP-GaBi_End-of-Life_Waste_elementary_Composition+2_16e9b2c5-3c44-11dd-ae16-0800200c9a66.jpg

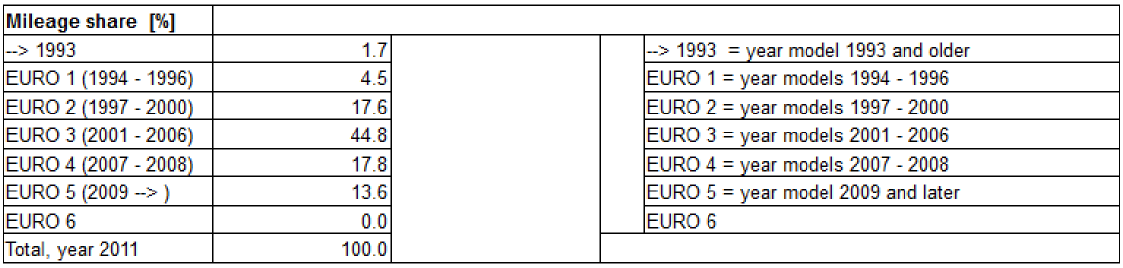
Appendix3 **Urban driving emissions and energy consumption**



	Energy consumption [MJ/tkm]		Energy consumption [MJ/km]		
	(50% load)	full loaded (19t load)	Empty	(50% load)	full loaded (19t load)
--> 1993	1.7	1.0	13	17	20
EURO 1 (1994 - 1996)	1.8	1.1	14	17	20
EURO 2 (1997 - 2000)	1.8	1.1	14	17	20
EURO 3 (2001 - 2006)	1.8	1.1	14	18	21
EURO 4 (2007 - 2008)	1.8	1.1	14	17	20
EURO 5 (2009 -->)	1.8	1.1	14	17	20
EURO 6					
Average, year 2011	1.8	1.1	14	17	21



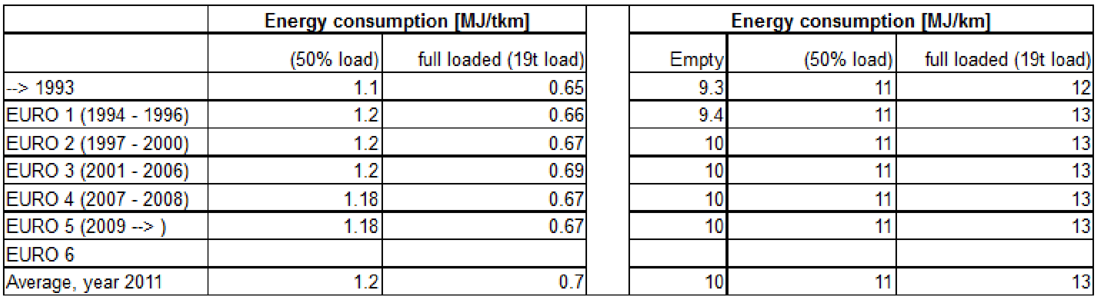
	Energy consumption [kWh/tkm]		Energy consumption [kWh/km]		
	(50% load)	full loaded (19t load)	Empty	(50% load)	full loaded (19t load)
--> 1993	0.48	0.29	3.7	4.6	5.5
EURO 1 (1994 - 1996)	0.49	0.29	3.8	4.7	5.6
EURO 2 (1997 - 2000)	0.50	0.30	3.8	4.8	5.7
EURO 3 (2001 - 2006)	0.51	0.31	3.9	4.9	5.8
EURO 4 (2007 - 2008)	0.50	0.30	3.8	4.8	5.7
EURO 5 (2009 -->)	0.50	0.30	3.8	4.8	5.7
EURO 6					
Average, year 2011	0.51	0.30	3.9	4.8	5.7



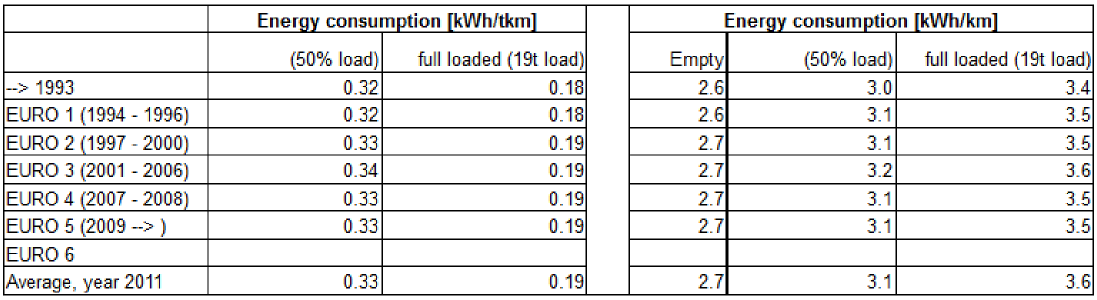
Mileage share [%]		
--> 1993	1.7	--> 1993 = year model 1993 and older
EURO 1 (1994 - 1996)	4.5	EURO 1 = year models 1994 - 1996
EURO 2 (1997 - 2000)	17.6	EURO 2 = year models 1997 - 2000
EURO 3 (2001 - 2006)	44.8	EURO 3 = year models 2001 - 2006
EURO 4 (2007 - 2008)	17.8	EURO 4 = year models 2007 - 2008
EURO 5 (2009 -->)	13.6	EURO 5 = year model 2009 and later
EURO 6	0.0	EURO 6
Total, year 2011	100.0	

http://lipasto.vtt.fi/yksikkopaastot/tavaraliikennee/tieliikennee/kamaanskatue.htm

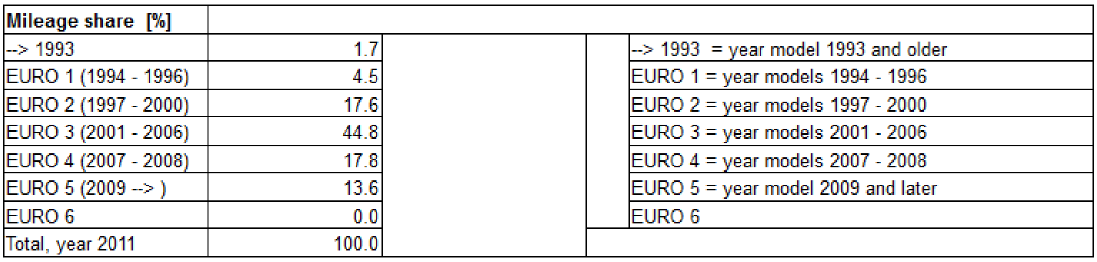
Appendix4 **Highway driving**



	Energy consumption [MJ/tkm]		Energy consumption [MJ/km]		
	(50% load)	full loaded (19t load)	Empty	(50% load)	full loaded (19t load)
--> 1993	1.1	0.65	9.3	11	12
EURO 1 (1994 - 1996)	1.2	0.66	9.4	11	13
EURO 2 (1997 - 2000)	1.2	0.67	10	11	13
EURO 3 (2001 - 2006)	1.2	0.69	10	11	13
EURO 4 (2007 - 2008)	1.18	0.67	10	11	13
EURO 5 (2009 -->)	1.18	0.67	10	11	13
EURO 6					
Average, year 2011	1.2	0.7	10	11	13



	Energy consumption [kWh/tkm]		Energy consumption [kWh/km]		
	(50% load)	full loaded (19t load)	Empty	(50% load)	full loaded (19t load)
--> 1993	0.32	0.18	2.6	3.0	3.4
EURO 1 (1994 - 1996)	0.32	0.18	2.6	3.1	3.5
EURO 2 (1997 - 2000)	0.33	0.19	2.7	3.1	3.5
EURO 3 (2001 - 2006)	0.34	0.19	2.7	3.2	3.6
EURO 4 (2007 - 2008)	0.33	0.19	2.7	3.1	3.5
EURO 5 (2009 -->)	0.33	0.19	2.7	3.1	3.5
EURO 6					
Average, year 2011	0.33	0.19	2.7	3.1	3.6



Mileage share [%]		
--> 1993	1.7	--> 1993 = year model 1993 and older
EURO 1 (1994 - 1996)	4.5	EURO 1 = year models 1994 - 1996
EURO 2 (1997 - 2000)	17.6	EURO 2 = year models 1997 - 2000
EURO 3 (2001 - 2006)	44.8	EURO 3 = year models 2001 - 2006
EURO 4 (2007 - 2008)	17.8	EURO 4 = year models 2007 - 2008
EURO 5 (2009 -->)	13.6	EURO 5 = year model 2009 and later
EURO 6	0.0	EURO 6
Total, year 2011	100.0	

Appendix5 **Characterization factors of different impact categories**

Global Warming Potential			
Pollutant	CO_2	CH_4	N_2O
Characterization factor values	1	21	310

Acidification			
Pollutant	SO_2	NO_x	NH_3
Characterization factor values	1	0.7	1.88

Human Toxicity				
Pollutant	SO_2	NO_x	PM	NH_3
Characterization factor values	0.096	1.2	0.246	0.1