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**Directions of future developments in waste recycling**

Kestävän kierrätyksen tulevaisuuden kehityssuuntia. **Malin Meinander (ed.), Ulla-Maija Mroueh (ed.), John Bacher, Jutta Laine-Ylijoki, Margareta Wahlström, Johannes Jermakka, Nina Teirasvuo, Hannele Kuosa, Maria Törn, Johanna Laaksonen, Jukka Heiskanen, Juha Kaila, Hanna Vanhanen, Helena Dahlbo, Kaarina Saramäki, Timo Jouttijärvi, Tuomas Mattila, Risto Retkin, Pirke Suoheimo, Katja Lähtinen, Susanna Sironen, Jaana Sorvari, Tuuli Myllymaa, Jouni Havukainen, Mika Horttanainen & Mika Luoranen.** Espoo 2012. VTT Technology 60. 86 p. + app. 80 p.

# Abstract

This publication summarises the results and conclusions of the research project Advanced Solutions for Recycling of Complex and New Materials. The aim of the project has been to create an understanding of the future development needs of waste recycling and management by conducting an in-depth analysis of five selected waste value chains. The chains analysed were:

- construction and demolition (C&D) waste
- commercial and industrial waste (C&I)
- household waste / municipal solid waste (MSW)
- waste electrical and electronic equipment (WEEE)
- end-of-life vehicles (ELV).

The main emphasis was on the analysis of the five waste chains including technologies, material utilisation and losses, as well as environmental and economic analyses of the current systems. The current and future requirements of the Finnish operational and business environment were also studied. The findings of the project are to be applicable in the planning and implementation of future development projects, as well as in decision making by various actors of the sector.

The main methodologies used in this study were literature reviews, data collection, interviews and waste chain modelling; material flow analysis (MFA), life cycle assessment (LCA) focusing on climate impacts and resource use, and life cycle cost analysis (LCC). Value formation was studied in WEEE and ELV chains.

The operational environment in the waste management chains is affected by various environmental and other policies and regulations, demand and supply as well as raw material prices. Cultural aspects and people's attitudes are also important, especially because the waste market will be increasingly global.

The rising prices of raw materials and stricter recycling targets are expected to affect product design and development of innovations in the field. Increased recycling calls for systemic thinking and improved waste chain management with more efficient processes and technologies. Integrated modelling concepts and analysis of future scenarios are needed for assessment of the economic viability of the recycling solutions. For example, development of new presorting and pretreatment concepts could improve both the quality and quantity of products. Management of the entire treatment chain calls for real-time monitoring methods integrated with on-line quality control.

**Keywords** waste chain management, material flow analysis, LCA, commercial and industrial waste, municipal waste, construction and demolition waste, waste electrical and electronic equipment, end-of-life vehicles, future development

**Kestävän kierrätyksen tulevaisuuden kehityssuuntia**

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# Tiivistelmä

Tässä julkaisussa on esitetty tutkimusprojektin ”Advanced Solutions for Recycling of Complex and New Materials” tuloksia ja johtopäätöksiä. Hankkeen tavoitteena oli luoda käsitys jätehuollon tulevaisuuden kehitystarpeista syventymällä viiteen jäteketjuun:

- rakennus- ja purkujäte (C&D)
- kaupan ja teollisuuden jätteet (C&I)
- kotitalousjäte / yhdyskuntajäte (MSW)
- sähkö- ja elektroniikkaromu, SER (WEEE)
- romuautot (ELV).

Tutkimuksessa analysoitiin Suomen jäte- ja kierrätysalan arvoketjuja ja toimintaympäristöä tavoitteena luoda ymmärrystä tulevaisuuden kehittämistarpeista. Valittuja arvoketjuja tarkasteltiin erityisesti seuraavista näkökulmista: teknologiat, materiaalien hyödyntämisasteet ja materiaalihäviöt sekä merkittävimmät ympäristövaikutukset ja taloudelliset vaikutukset. Tuloksia voidaan hyödyntää tulevaisuuden suunnittelu- ja kehitysprojekteissa. Ne tukevat myös jäte- ja kierrätysalan päätöksentekoa.

Tutkimusmenetelminä käytettiin kirjallisuusselvityksiä, tiedonlouhintaa, haastatteluja sekä arvoketjujen mallinnusmenetelmiä: materiaalivirta-analyysit, elinkaarianalyysit keskittyen erityisesti ilmastovaikutuksiin ja luonnonvarojen käyttöön sekä elinkaarikustannusten arviointi esimerkkitapauksessa. Lisäksi tarkasteltiin arvonmuodostusta SER- ja WEEE-ketjuissa.

Kierrätys- ja jätehuoltoalan toimintaympäristöön vaikuttavat erityisesti lainsäädäntö, kysynnän ja tarjonnan kehittyminen sekä materiaalien ja energian hinnat. Myös kulttuuri- ja asenneympäristö on tärkeä, varsinkin siksi, että alan markkinat ovat yhä enemmän maailmanlaajuisia. Kuten muillakin aloilla, sidosryhmien merkitys on kasvamassa.

Raaka-aineiden hintojen nousun ja tiukkenevien kierrätystavoitteiden voidaan tulevaisuudessa odottaa johtavan uusien innovaatioiden syntymiseen ja käyttöönottoon sekä vähitellen kierrätystä tukevien tuotesuunnittelumenetelmien kehitykseen. Kierrätyksen tehostaminen edellyttää systeemistä ajattelua, jätevirtojen hallintamenetelmien kehittämistä sekä tehokkaampia erottelu- ja lajitteluteknologioita koko keräys- ja käsittelyketjuun. Taloudellisten edellytysten arviointiin tarvitaan eri näkökulmia yhdistäviä mallinnuskonsepteja ja tulevaisuuden skenaarioiden tarkastelua. Tuotteiden saantoa ja laatua voidaan parantaa mm. kehittämällä uusia konsepteja esilajittelun ja -erottelun tehostamiseen. Koko käsittelyketjun ja tuotteen laadun hallitsemiseksi tarvitaan eri virtojen reaaliaikaista monitorointia yhdistettynä online-laadunvalvontamenetelmiin.

**Asiasanat** waste chain management, material flow analysis, LCA, commercial and industrial waste, municipal waste, construction and demolition waste, waste electrical and electronic equipment, end-of-life vehicles, future development

# Preface

This publication summarises the results and conclusions of the research project Advanced Solutions for Recycling of Complex and New Materials. The aim of the project was to analyse the current situation of selected waste value chains as well as the demands on the current and future operational environment. Based on the results, an analysis of challenges and development needs in these value chains was made, and future development opportunities identified.

The waste value chains analysed were: Recycling and utilisation of construction and demolition (C&D) waste; Recycling and utilisation of commercial and industrial waste (C&I); Recycling and utilisation of household waste / municipal solid waste (MSW); Recovery of valuable materials from waste electrical and electronic equipment (WEEE); and Recycling and utilisation of End-of-Life vehicles (ELV). The project produced several research reports which are listed in Appendix 1.

The project was funded by Tekes (Finnish Funding Agency for Technology and Innovation) a group of companies and participating research institutes. The research partners and their main duties in the project were:

- VTT Technical Research Centre of Finland: Coordinator for the project with main responsibility for the analysis of MSW and C&D value chains
- Aalto University School of Science and Technology Lahti Center (AALTO) with main responsibility for the WEEE, C&I and ELV value chains
- The Finnish Environment Institute (SYKE), responsible for the analysis of strategies and legislation, Life cycle analysis (LCA and LCC), BAT analysis, and assessment of hazardous substances
- Lappeenranta University of Technology (LUT), responsible for the Waste to Energy opportunities in the value chains mentioned above.

The Steering Group for the project consisted of the following people: Antero Vattulainen, Kuusakoski Oy; Toni Andersson, Ekokem Oy Ab; Tuomo Joutsenoja, Rudus Oy; Ilkka Kojo, Outotec Oy; Markku Lehtokari, Turun Seudun Jätehuolto Oy; Marko Mäkikyrö, Ruukki Metals Oy, Pekka Pouttu, Kiertokapula Oy; Arto Ryhänen, Jätekukko Oy, Jukka Ylijoki, Metso Automation Oy; Asko Vesanto, Tekes; Jatta Jussila, CLEEN Oy; Eva Häkkä-Rönnholm, VTT; Juha Kaila, Aalto University; Tuuli

Myllymaa, Finnish Environment Institute; Mika Horttanainen, Lappeenranta University of Technology; and Ulla-Maija Mroueh, VTT, secretary.

The research group would like to express their gratitude to the steering group and other representatives of the companies for their support during the project, as well as collaboration in the definition of waste value chains and delivery of process data needed in the analysis.

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# 1. Introduction

Waste management is in a state of rapid change. In developed countries the transition from landfill disposal to energy and material recovery is already in full swing, and the current trend is towards more efficient material recovery and recycling processes. For example, according to the 'Roadmap to a resource-efficient Europe' (EC COM (2011) 571 Final) ‘by 2020 waste will be managed as a resource. Recycling and reuse of waste will be economically attractive for public and private actors, energy recovery is limited to non-recyclable materials and landfilling is virtually eliminated’.

Realization of these targets requires extensive development at both a technological and system level. One of the biggest challenges is the growing complexity of the products and related waste flows which makes recycling even more complicated nowadays. On the other hand, the waste management market in developing countries is also growing rapidly, and at least some of these countries have the possibility and the will to introduce advanced technologies. The radical changes in the business environment are an obvious opportunity for companies which are able to be in the forefront of the development of new technologies and services adapted to the demands of a changing business environment.

The aim of the project has been to create an understanding of the future development needs of waste management by conducting an in-depth analysis of selected waste management chains, beginning with waste generation and ending with the production of products and materials on the market. The selection of the waste management chains for analysis was based on the business expectations from the perspective of Finnish recycling and waste management actors. Both the current situation and especially future international and domestic business potential were considered. The waste management chains analysed are Construction and demolition waste (C&D), Commercial and industrial waste (C&I), Municipal solid waste (MSW), Waste electrical and electronic equipment (WEEE), and End-of-Life vehicles (ELV).

A systematic modelling approach was used, which has resulted in identification and definition of the most significant development goals of each chain. One of the targets of the project has been to create a basis for a research programme or research projects commercialising the research findings.

Several reports have been produced during the project, and the aim of this final report is to combine and summarize all these reports. A list of all reports produced during the project can be found in Appendix 1. The analysis reports can be obtained upon request from the responsible research organisation. In addition to the analysis reports, several scientific publications are planned, based on the results of the project. Furthermore, many conference presentations have been held and are planned based on the findings of the NeReMa project.

The findings of the project are to be applicable in the planning and implementation of future development projects, as well as in the decision-making of various actors in the recycling and waste management sector. Both this project and the future research programme or projects generated by it enable the development of high-level competence as well as sustainable technologies, products and services to meet future market requirements. Thus they promote the competitiveness of the Finnish recycling industry on the international and domestic market.

This report includes an introduction to the Finnish operational and business environment for waste companies. The waste chains are presented, as are also the analysis results of the NeReMa project, including technologies, material utilisation and losses, as well as environmental and economic analyses of the current systems. Furthermore, the research group presents their observations on the prospects for future waste management, drivers and future opportunities for the waste management companies.

# 2. Operational environment

## 2.1 Policies and legislation

The waste management chains and the actors along the chain are affected by various environmental and other policies and regulations. Future drivers and trends have been identified at the global, EU and national level. The main focus in this chapter is on waste legislation. As Finnish waste legislation is being revised at the time of writing of this report, some issues are discussed at a general level.

Policies on material resources are at an early stage of development; however, the already comprehensive set of EU waste policies has been further developed in the past few years. The Thematic Strategy on the Prevention and Recycling of Waste and the revised Waste Framework Directive (EU, 2008a) are important milestones. The Mining Waste Directive (EU, 2006a), the Batteries Directive (EU, 2006b), the European Commission's Communication on future steps in bio-waste management in the European Union (EU, 2010) and the European Commission's Communication on Better Ship Dismantling (EU, 2008b) were issued to close loopholes in the Waste Policy Framework concerning these specific wastes. A number of directives tackling specific waste streams have reached the phase of practical implementation in the member states — the WEEE Directive (EU, 2003), the End-of-life Vehicles Directive (EU, 2000) and the Landfill Directive (EU, 1999) in the case of biodegradable municipal wastes.

The Waste Framework Directive (EU, 2008) establishes a five-level waste hierarchy, at the top of which is prevention. The order of priority in waste prevention and management legislation and policy is: a) prevention; b) preparing for re-use; c) recycling; d) other recovery, e.g. energy recovery, and e) disposal.

Finnish waste legislation is largely based on EU legislation. The new waste law and the waste decree which specifies some issues in the waste act came into force on May 2012. Important issues included in the reformation of the Finnish waste legislation are:

*Producers' responsibilities* in the waste management of packaging are extended. The producer will be responsible for the waste management of packages and its costs. Minimum requirements for the number of collection points for consumers in order to guarantee a sufficient level of service in the whole country are to be defined later by a decree.

The new Waste Act proposes an expanded responsibility for *waste accounting* (118–119§). Producers with at least 100 tonnes of waste must be aware of waste amounts from production and products. Reporting is not required. The waste accounting may indirectly encourage innovations in the field of recycling through enhanced knowledge of waste streams and material efficiency.

*End of Waste criteria* under which waste could cease to be waste. The purpose of defining end of waste criteria is to facilitate and promote recycling, ensuring a high level of environmental protection, reducing the consumption of natural resources and the amount of waste sent for disposal. End of waste criteria will be applicable to specific waste streams. So far the criteria for iron, steel and aluminium scrap have been adopted (Council Regulation EU No 333/2011). Criteria for scrap copper, waste paper, waste glass, biowaste and plastic waste are under preparation. EU regulations are binding in their entirety and directly applicable in Member States.

*Ban on landfilling organic wastes* to be included in the government decree on landfill sites is being prepared by the Ministry of Environment. Organic waste is that able to decompose biologically or thermally such as biodegradable waste and plastic and rubber waste. The ban is supposed to apply from 2016. The decree will define limit values for organic carbon in waste, and waste tests are required. The ban means that waste management companies will be required either to recycle organic waste, or to utilize it as an energy source, either by burning it directly, or using it to produce methane through decomposition.

*Tax on waste* is governed by the new Waste Tax Act (1126/2010) which came into force from the beginning of the 2011. Tax on waste is levied on waste deposited at public and private landfill sites. The tax is charged at a rate of EUR 40 per tonne and from the year 2013 it will be EUR 50 per tonne. (Waste Tax Act 1126/2010)

The new waste act specifies the role of *material efficiency in environmental permits*. Environmental permits will contain necessary regulations on wastes and reduction of their quantity and harmfulness. In addition, efficiency in the use of materials must be taken into account as needed. The Ministry of Environment will publish guidelines to promote material efficiency in environmental permits.

***The waste hierarchy***

*The Finnish and European waste legislation is largely based on the waste hierarchy. It is a theory of the desirability of different waste management and treatment strategies. The first objective according to the waste hierarchy is to avoid waste generation. This can be done through e.g. source reduction (product and process optimisation), extended producer responsibility, as well as by influencing consumer attitudes. Another method of waste reduction is reuse, which is to use an item more than once. This includes conventional reuse where the item is used again for the same function, as well as new-life reuse where it is used with a new function.*

*When the waste is already generated, then material recycling is seen as the best solution for waste treatment. Energy recovery is optional if the material recovery is very expensive in comparison to other waste treatment methods or more energy intensive than the production of virgin raw materials. The best treatment alternative can be found through LCA and economic analyses of the treatment alternatives. The least favourable alternative is final disposal. But if disposal is necessary due to lack of a suitable treatment method, disposal must be carried out in a sustainable manner.*


*The waste hierarchy refers to the "3 Rs" of waste management, i.e. reuse, reduce, and recycle. These classify waste management strategies according to their desirability. The aim of the waste hierarchy is to optimise the benefits from products and to generate the minimum amount of waste.*

## 2.2 Business environment

In 2003 the revenue of the Finnish waste management sector was approximately MEUR 400, of which 45% and 55% came from the waste management and recycling sectors respectively. The two main services of the waste management sector are collection and treatment. Although the waste volumes are not forecast to increase in Finland, on-site sorting and recycling is to increase. As seen in many European countries with maturing waste management, the most successful companies are focusing on an improved service level and holistic waste management solutions. In recent years Finnish recycling companies have expanded their activities abroad, mainly to neighbouring countries, but also to e.g. China. (Huhtinen et al., 2007.)

European waste volumes are continuously increasing, Frost & Sullivan (2010) estimate that the MSW generation will increase by 25% between 2005 and 2020 in EU-25. However, the growth rate is slowly diminishing and soon the waste volumes may also diminish. The value of the waste management market will still continue to increase, both due to increasing recycling and recovery rates, but also due to the increased service supply and role of technology providers as well as the increasing market value of recyclables (Frost & Sullivan, 2006).

Globally, the waste management market will grow, especially in the emerging and developing countries of Asia, South America and later on also in Africa, where the simultaneous growth of population and GDP lead to a strongly increasing amount of waste. According to the estimates of the World Bank, the production of municipal waste in 2007 alone was 3.8 million tonnes per day in developing countries and 1.4 million tonnes per day in developed countries (UNRDC, 2009). The standard of waste management is related to the GDP/person, enabling the development of waste infrastructure and the introduction of more advanced technologies.

As certain raw materials are becoming scarcer, while energy and fuel prices are increasing, production costs are increasing. Often the production and use of recovered raw materials requires a smaller energy input than the production and use of virgin raw material. As also the prices of recovered materials are often low, manufacturing industry is increasingly favouring the replacement of virgin raw materials with recovered materials. In the future this trend is forecast to grow stronger, further increasing the benefits of on-site separation and recycling.

Waste is increasingly becoming a good which is traded around the world. The international waste trade is increasing constantly; in 2005, waste import to Finland was approximately 0.8 Mt and export 1 Mt (SYKE, 2003; 2005). The market drivers of demand and prices of recyclables vary substantially between different materials. The market prices of recyclables in general follow the world market prices of corresponding virgin raw materials. The volatility of market prices of recyclables has, however, always been bigger compared with the prices of virgin raw materials. The supply-demand is one of the most important factors determining the price level. Price alternations are commonly interconnected with alternations in supply, although other factors, such as politics and instabilities, as well as oil and energy prices, tend to impact the market prices of most goods. The recycling market is, however, far from perfect. Several market inefficiencies have been identified which affect both the demand and the price of recyclables, as described in Table 1.

**Table 1.** Potential sources of recyclables market inefficiency (OECD, 2006).

| Causes of market inefficiency | Explanation |
|---|---|
| Transaction costs in secondary material markets | Arises from the diffuse and irregular nature of waste generation. May also arise from the heterogeneous nature of secondary materials. |
| Information failures related to waste quality | Arises from the difficulty for buyers to detect waste quality, and the relative ease with which sellers can conceal inferior quality waste. |
| Consumption externalities and risk aversion | Perceived costs associated with the quality of final goods derived from secondary materials relative to those derived from virgin materials. |
| Technological externalities related to products | Complexity of recycling due the technical characteristics of the recyclable material and products from which secondary materials are derived. |
| Market power in primary and secondary markets | Substitution between primary and recyclable materials may be restricted due to imperfect competition and strategic behavior on the part of firms. |

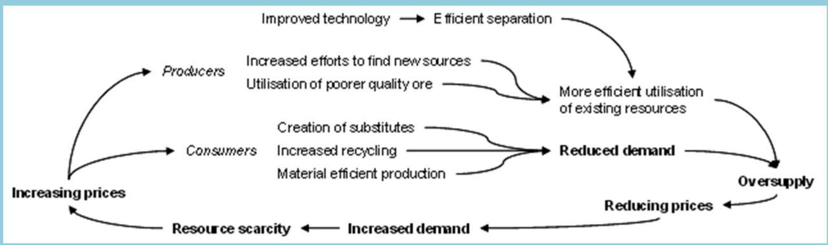
The increasing value and importance of recycling in Europe are related to the following factors (Fisher et al., 2011):

- The unit prices have increased in current prices for a decade until the crisis at the end of 2008, and they have recovered since then.
- The booming Asian economy has needed more recyclables. The increasing Asian demand has not only been positive for the unit prices of the recyclables, it has also consumed larger and larger amounts of recyclables generated in the EU.
- Different EU directives that specify an increasing percentage of specific waste types to be recycled in EU Member States have led to an increasing amount of recyclables being put on the market.

With the exception of metal scrap and fibres (paper and cardboard), most of the supply in recyclables in Europe is regulation-driven. Regulation affects the supply in two different ways. The key mechanisms are the mandatory collection and recycling requirements either directly concerning specified materials or indirectly through extended producer responsibility. Another mechanism is the landfill ban which has already been adopted in several European countries, and which aims to force materials higher in the waste hierarchy and thus also supports material recycling.

***The global markets for scrap metals***

*Scrap metal can be recycled into the same quality new metal, and the energy consumption of the recycling process is significantly lower than of the virgin material. Therefore, a significant part of the world's metals are produced from recycled waste materials. The scrap metal market follows the dynamics of the global metal markets; the main fluctuations are due to changes in supply and demand. It is not only the production rate controlling supply, but also existing and future stocks. The price correlates with the future prospects of availability and moves a little ahead of actual availability. As the production of metal from mining of ore to the final raw material is quite energy-intensive, metal prices correlate with energy prices. The central factors affecting the supply an d demand and market prices are illustrated in the figure. (Korppinen, 2010; Heiskanen, 2009)*




*The central factors affecting the supply, demand and market prices of metals. The major economies like the USA, China and Japan have a great influence on global metal market prices. The impact of the Chinese market is continuously growing on behalf of the US market. Lately the Chinese markets have been responsible for up to 90% of total market growth. (Korppinen, 2010)*

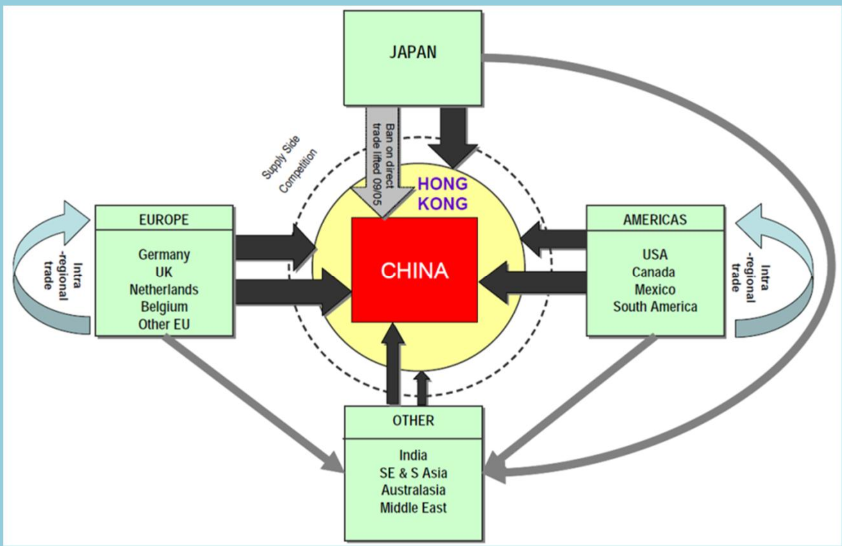
***The global markets for plastic waste***

*Since 1950 the annual global plastic production has increased on average approx. 10%. Increased consumption impacts the demand for both virgin and recovered raw materials, while higher energy and oil prices will increase the price of virgin plastic. Plastic recycling has grown in Europe and China during the last decade; in Europe mainly due to the implementation of stricter waste legislation and in China due to the need for a cheap plastic raw material. Plastic recycling is quite a labour-intensive process, and China is a major plastic recycler due to its low labour costs. (WRAP, 2006)*

*Most of the plastic waste is not suitable for recycling as it is dirty and contains several different materials and combinations. Cleaning of waste plastic is commonly a costly process, and separation of different plastic types is labour-intensive if it is even possible. Thus, plastics waste is mainly used for energy recovery. Sorted PET bottles are homogeneous and quite clean; thus, PET bottles make up the majority of the recycled household plastic waste. Sorted C&I plastic waste can also have an adequate quality for recycling. (WRAP, 2006)*

***Plastic waste exports to China***

*The EU exports plenty of plastic waste to China, which has an increasing demand for plastic waste and is a major player on the waste plastics market; WRAP (2006) estimates that 70% of the global waste plastics end up in China. Currently the Chinese import of plastic waste is increasing by 500-1,000 kt annually. The global waste plastic market is illustrated in the Figure below, showing that the majority of the global plastic waste ends up in China. The global markets for recycled plastic waste is highly dependent on Chinese legislation; currently it is possible to export unwashed plastic waste to China, but if Chinese legislation requires the plastic to be washed before export the price of the European waste plastic will increase significantly due to the higher European labour costs, eliminating exports to China.*




*The global waste plastics market; a lot of the waste plastics is transported through Hong Kong to China, mainly due to the easier customs procedures of Hong Kong. (WRAP, 2006)*

# 3. Analysis of selected waste chains

## 3.1 Waste chains and analysis methods

The waste chains analysed were:

- **Construction and demolition waste (C&D)** is all waste other than regular household waste produced at a construction site. It neither includes waste reused directly on site without any processing nor waste generated by the construction industry off-site.
- **Commercial and industrial waste (C&I)** is the waste produced by institutions, commerce and industry, excluding production and process waste, and which is comparable to MSW. It is often collected and treated, and usually reported together with MSW.
- **Municipal solid waste (MSW)** covers waste from households, garden waste, street sweepings, and the contents of litter containers, as well as similar commercial and industrial waste.
- **Waste electrical and electronic equipment (WEEE)** originates from households and industry, it is a very versatile waste fraction and includes a vast variety of different electrical and electronic items.
- **End-of-Life vehicles (ELV)** is motor vehicles which have reached the end of their useful lives and are collected for controlled dismantling.

Each waste chain analysis consisted of seven subtasks:

- Definition of the waste operational chain and identification of future trends and requirements.
- Market analysis of waste management and recycling technologies, systems and services, recycled waste fractions and other marketable products as well as the compilation of economic data.
- Collection of data on waste generation and composition, current recycling and quality demands set by legislation, end-users, etc.

- Technical analysis, including current technologies and processes, in each phase of the waste chain, and a more exact schematic description of the waste chain. The challenges of the current system were pointed out, as well.
- Formulation and definition of base case (current situation) in detail, material flow analysis (MFA), preliminary LCA and cost analysis of the base case.
- Comparison of the waste chain (base case) with relevant BREF documents and other BAT information as well as a deeper BAT analysis of one waste chain.
- Recommendations and insights for further development initiatives and research goals of the waste chains studied.

The most important methods used in the waste chain analysis were:

- Literature review, data collection and interviews for the purpose of making an accurate description of the waste chain and the operational environment.
- Material flow analysis (MFA), a descriptive approach used for a systematic assessment of material flows and stocks in waste operational chains. The level of detail varied depending on the target level of the chain analysis and the availability of data. In most cases the process concepts had to be simplified because of the lack of data at unit process level. MFA was also used as a starting point in life cycle assessment (LCA), energy flow analysis and in the comparison of material flow development scenarios. The MFA analysis tool was STAN2 software developed by the Vienna University of Technology and is presented in Appendix 2.
- The waste-to-energy (WTE) technologies examined included firing by grate, fluidized bed or rotary kiln, pyrolysis, gasification, digestion and fermentation.
- Life Cycle Assessment (LCA) is a comprehensive, quantitative approach to assessing the emissions, resources consumed and pressures on health and the environment of waste materials during their entire life cycle, from the ‘cradle’ to the ‘grave’. It also quantifies the indirect benefits of recovering materials and energy from waste. The objective of LCA was to provide an estimate of the potential impacts of the waste chains and to highlight the life cycle phases or waste flows causing the greatest contributions to their impacts. The environmental impacts considered the most relevant and hence important to be included in the LCA performed in the NeReMa-project were climate change (CC) impacts and the use of natural resources. Hazardous substances occurring in the waste chains were assessed quantitatively for the C&D and WEEE chains

- Environmental life cycle costing (LCC) is a method for evaluating the total economic effects of a process, product or technology. It follows the structure of environmental life cycle assessment (LCA) but looks at the internalized costs during the life cycle of the system studied. The theoretical assumptions of traditional LCC differ from LCA regarding, e.g., exclusion of non-market incidences (e.g., pollution) and the crucial role of timeframe (i.e., interest rates) in calculations.
- Best Available Techniques (BAT) describes the level of environmental management and environmental protection in industrial operations. Screening of waste chains from the BAT viewpoint was performed over C&D and WEEE chains.

### 3.1.1 Features of the selected operational chains

In the NeReMa project five waste operational chains have been analysed. In order to create the analyses, the operational features of the operational chain need to be examined. Besides the differing materials, also differing services, technologies and stakeholders have been identified for the waste chains. Figure 1 presents a generalisation of the waste operational chain and Tables 2–4 analysis of the features of the five selected operational chains.

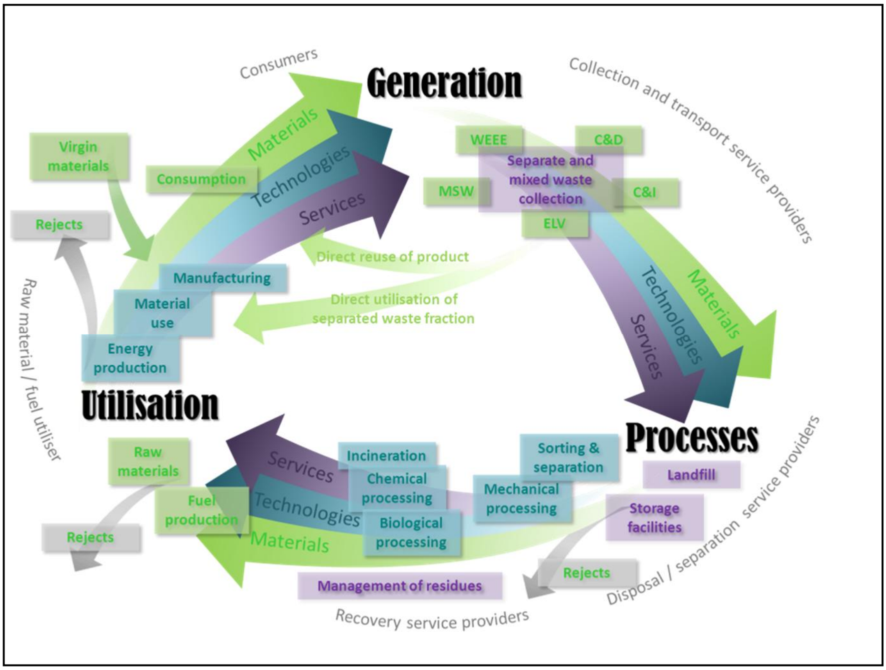



**Figure 1.** General description of the operational chains.

**Table 2.** Features of the generation stage of the five selected operational chains.

| Generation | C&D | C&I | MSW | WEEE | ELV |
|---|---|---|---|---|---|
| **Materials (waste fractions)** | • Miscallaneous<br>• Metals<br>• Mineral waste<br>• Wood<br>• Gypsum<br>• Energy waste | • Miscallaneous<br>• Paper<br>• Cardboard<br>• Biowaste<br>• Glass<br>• Metals<br>• Plastics<br>• Wood<br>• WEEE<br>• Energy waste<br>• Hazardous waste | • Miscallaneous<br>• Paper<br>• Cardboard<br>• Biowaste<br>• Glass<br>• Metals<br>• Plastics<br>• Wood<br>• WEEE<br>• Energy waste<br>• Hazardous waste | • WEEE unsorted<br>• WEEE (sorted)<br>-screens + TVs<br>-computer products<br>-freezers and fridges<br>-large items<br>-small items | End of life vehicles |
| **Technologies** | • Site sorting | • Pressers and bailers for the compaction of cardboard<br>• Site sorting<br>• Waste collection vehicles<br>• Deposit system for bottles<br>• Pallets | • Site sorting<br>• Waste collection vehicles | • Site sorting | |
| **Services** | • Waste collection and transport services | • Waste collection and transport services | • Waste collection points<br>• Waste collection and transport services | • Waste reception stations<br>• Transports | • Free pickups in the metropolitan area<br>• Reception Stations<br>• Transports |
| **Stakeholders**<br>**• Waste generator** | • Construction companies | • Industry and commerce | • Households | • Households and industry | • Households and industry |
| **• Responsibility** | • Construction companies | • Waste generator<br>• Municipality<br>• Producer responsibility | • Municipality<br>• Producer responsibility | • Producer responsibility | • Waste generator<br>• Producer responsibility |

**Table 3.** Features of the processes stage of the five selected operational chains.

| Processes | C&D | C&I | MSW | WEEE | ELV |
|---|---|---|---|---|---|
| Materials | • Sorted and processed waste fractions<br>• Rejects | • Sorted and processed waste fractions<br>• Rejects | • Sorted and processed waste fractions<br>• Rejects | • Rejects<br>• Iron and steel<br>• Plastics<br>• Copper<br>• Glass<br>• Aluminum<br>• PWB<br>• Wood and plywood<br>• Mineral waste<br>• Rubber<br>• Others | • Rejects<br>• Iron and steel<br>• Aluminum<br>• Zink, copper and lead<br>• Plastics<br>• Rubber<br>• Textiles<br>• Adhesive and paints<br>• Glass<br>• Fluids<br>• Miscallenous |
| Technologies | • Mechanical sorting<br>- crushing<br>- identification and separation<br>• Mechanical processing<br>• Incineration<br>• Landfilling | • MB treatment<br>• Mechanical sorting<br>- crushing<br>- identification and separation<br>• Washing<br>• Chemical processing<br>• Mechanical processing<br>• Incineration<br>• Biological processing<br>• Landfilling | • Mechanical sorting<br>- crushing<br>- identification and separation<br>• Washing<br>• Chemical processing<br>• Mechanical processing<br>• Incineration<br>• Biological processing<br>• Landfilling | • Manual dismantling<br>• Mechanical sorting<br>- crushing<br>- identification and separation<br>• Chemical processing<br>• Mechanical processing<br>• Incineration<br>• Landfilling | • Depollution<br>• Dismantling<br>• Mechanical sorting<br>- crushing<br>- identification and separation<br>• Mechanical processing<br>• Landfilling<br>• Storing |
| Services<br>• Storage | • No | • Paper and cardboard | • Paper and cardboard | • No | • ASR cannot be disposed of or incinerated, but is stored for future treatment |
| Stakeholders | • Recycling company<br>• Energy company<br>• Landfill operator | • Recycling company<br>• Energy company<br>• Landfill operator | • Recycling company<br>• Energy company<br>• Landfill operator<br>• Municipality | • Recycling company<br>• Energy company<br>• Landfill operator | • Recycling company<br>• Energy company<br>• Landfill operator |

**Table 4.** Features of the utilisation stage of the five selected operational chains.

| Utilisation | C&D | C&I | MSW | WEEE | ELV |
|---|---|---|---|---|---|
| Materials | • Raw materials<br>• Fuels<br>• Rejects | • Raw materials<br>• Fuels<br>• Rejects | • Raw materials<br>• Fuels<br>• Rejects | • Raw materials<br>• Fuels<br>• Rejects | • Raw materials<br>• Rejects |
| Technologies | • Manufacturing<br>• Energy recovery | • Manufacturing<br>• Energy recovery | • Manufacturing<br>• Energy recovery | • Manufacturing<br>• Energy recovery | • Manufacturing<br>• Energy recovery |
| Services | • Transport services | • Transport services | • Transport services | • Transport services | • Transport services |
| Stakeholders | • Producers<br>• Energy companies<br>• Consumers | • Producers<br>• Energy companies<br>• Consumers | • Producers<br>• Energy companies<br>• Consumers | • Producers<br>• Energy companies<br>• Consumers | • Producers<br>• Consumers |

### 3.1.2 Properties of selected waste chains

The selected waste chains have been analysed with MFA to study the current treatment methods and material potential. A short presentation of the characteristics of the waste chains is given below; more detailed descriptions can be found in Appendices 3–7.

#### 3.1.2.1 C&D waste

It is estimated that approximately 2 Mt of C&D waste was generated from construction sites in 2007 in Finland. Figure 2 illustrates the material content of the C&D stream, and Figure 3 the results of the MFA analysis. The main materials utilised from the C&D stream are metals, which are sold as scrap to be used as raw materials, as well as mineral waste, which is used mainly in infrastructure construction and as aggregates in concrete production. C&D is commonly quite mixed and contaminated, which complicates the material recovery.

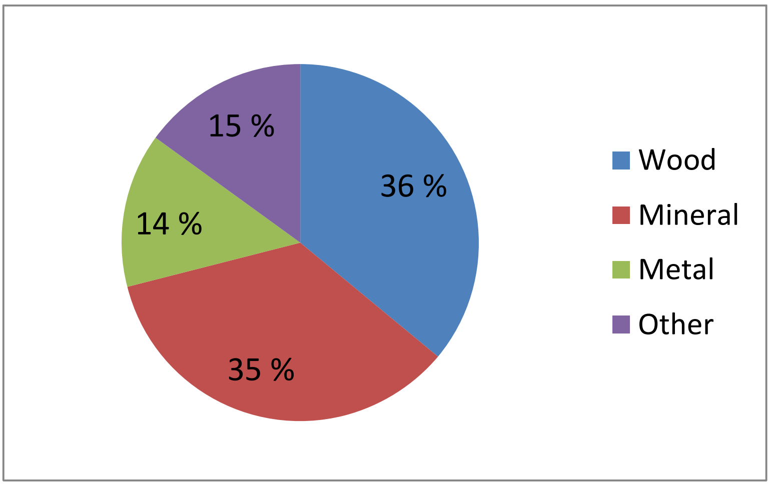



**Figure 2.** The average material content of the C&D chain. Others include e.g. gypsum, glass, plastic, packaging, mixed waste and hazardous waste.

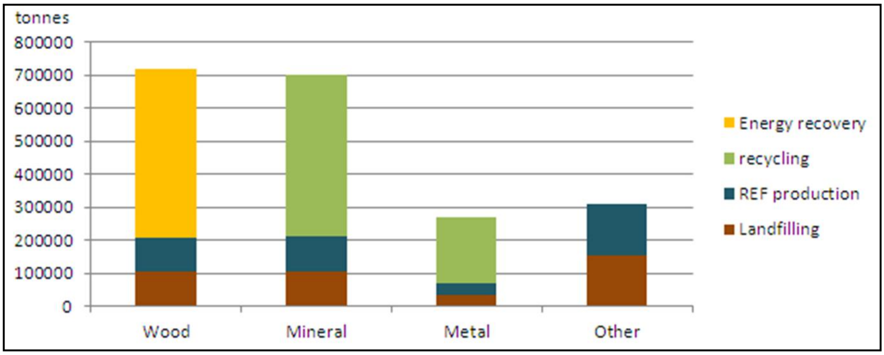



**Figure 3.** Results from the MFA analysis of C&D waste generation and treatment. Others include e.g. gypsum, glass, plastic, packaging, mixed waste and hazardous waste. After treatment, approximately 38% of the C&D stream is recycled as material, 35% recovered as energy, 6% utilized at landfills and 21% landfilled.

The main hazardous substances in C&D waste are phenols, asbestos, lead-based paints (LBP), polychlorinated biphenyls (PCB) and polycyclic hydrocarbons (PAH) (Monier et al., 2011). The use of asbestos, PAHs, LBPs and PCBs is restricted, and asbestos and PCBs are required to be collected separately but may still enter the mixed C&D waste stream. An important characteristic of the hazardous substances in construction and building products is the relatively long life span of the articles, also their use in a wide range of building products (OECD, 2011). The quantity of hazardous wastes in C&D waste is around 1%, but they can hinder the recycling of materials. Hazardous substances may be released into the environment for example during the demolition of buildings and the crushing and sieving of C&D waste. Potentially hazardous substances entering the environment increases when mixed C&D waste is treated outside. Studies have shown that hazardous substances, e.g. heavy metals, can also leach from landfilled C&D waste (Fatta et al., 2003; Hellman & Isoaho, 2006).

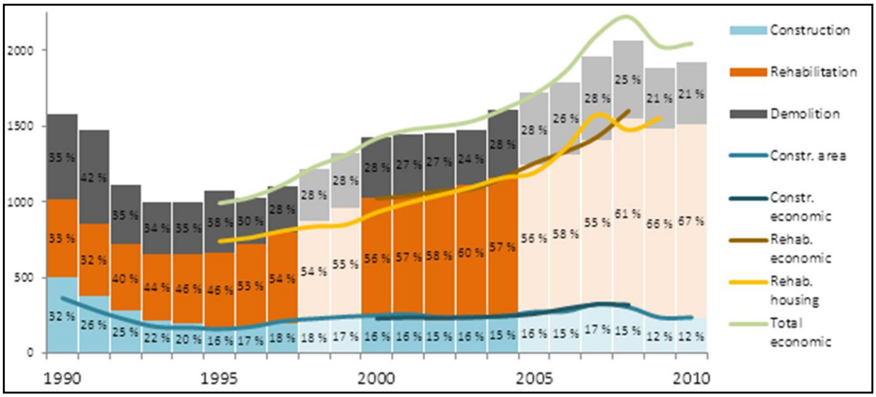



**Figure 4.** Estimations of C&D waste from construction, renovation and demolition activities in Finland [1000 t/a] 1990–2010 (Perälä et al., 2006; Perälä & Nippala, 1998; Statistics Finland 2011a, 2011b; Eurostat, 2010).

Figure 4 presents C&D waste generation trends in Finland in 1990–1997 and 2000–2004, and indicates that rehabilitation activities have grown while construction and demolition activities have been rather stable since 1995. It can be assumed on the basis of the age distribution of the Finnish housing stock that rehabilitation activities will continue to grow. Rehabilitation activities generate more wood and metals, but less minerals than the other C&D activities. On the other hand, large apartment buildings from the 1960s and 1970s are getting older and increased demolition might generate more minerals (Kojo & Lilja, 2011). Table 5 presents the current composition of C&D waste, as well as estimations for two future scenarios.

- Scenario 1 presents increased renovation while demolition remains stable. The wood fraction would increase as well as metal content, while minerals would decrease.
- Scenario 2 presents increased demolition while renovation remains stable. The mineral fraction would increase, while wood and metal would decrease.

**Table 5.** The composition of current state and two scenarios.

| | Current | Scenario 1 | Scenario 2 |
|---|---|---|---|
| Metals % | 13.5 | 15 | 10 |
| Minerals & Concrete % | 35 | 20 | 50 |
| Wood % | 36 | 45 | 20 |
| Other % | 15.5 | 20 | 20 |

In Figure 5 a comparison of treatment methods of the current state and two scenarios have been presented. The major difference in the two scenarios is that Scenario 1 has a higher energy utilization rate than Scenario 2. Considering that EU Waste Framework directive (EU, 2008a) requires 70% material utilization by 2020, neither scenario will achieve this without changes in processing and in sorting. In Scenario 1 a considerable amount of the waste is wood (45%), which is utilized as energy. This means, that with current treatment methods, the 70% material utilization cannot be achieved rationally in Scenario 1. Even though the wood fraction would decrease below 30%, the processing to achieve 70% material utilization would be extremely challenging since the amount of REF produced in the treatment of miscellaneous waste is too high. This means that, in order to achieve the requirements of the directive, the focus of the C&D waste treatment needs to change from REF production and energy utilization into material utilization.

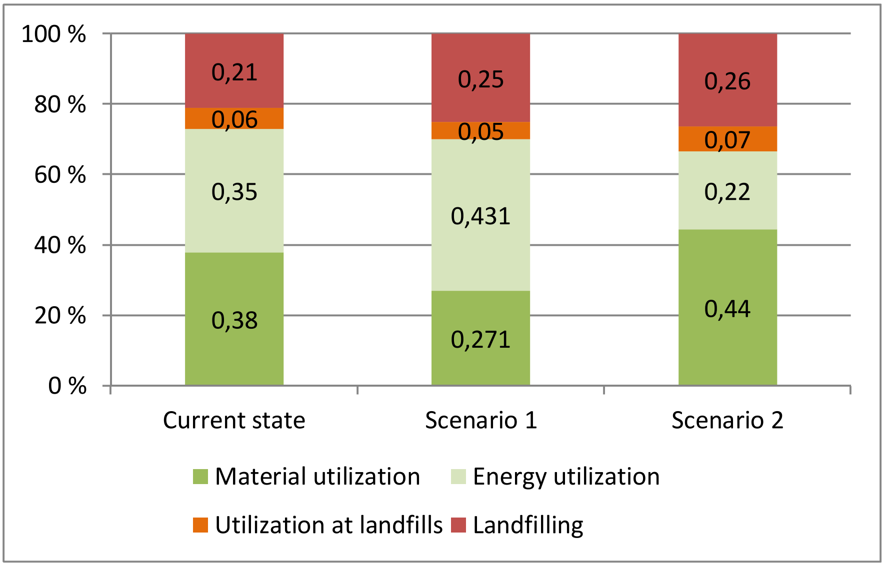



**Figure 5.** Results from the MFA analysis of the current and two alternative future waste generation scenarios.

***Characteristics of C&D waste***

*A typical feature of C & D waste is that it is not continuously generated, and its characteristics varies due to the site-specific conditions. C&D waste is commonly very heterogeneous, with a high mineral composition and a low content of combustible and biologically degradable matter. (Monier et al., 2011) In northern Europe, wood is the main construction material, whereas brick and concrete dominate elsewhere. As energy recovery is not seen as recycling in the EU waste framework directive (EU, 2008a), Finland will have some problems achieving the 70% recycling rate.*

*C&D wastes are generated at three types of construction sites: renovation (27%), demolition (57%) and construction (16%) (Environment, 2009). Each of these sites produces waste with different composition and characteristics. The waste streams of construction sites are mostly clean material surpluses which are not mixed and contaminated. Demolition and renovation waste, on the other hand, is mixed and contaminated and thus also more difficult to recover. (Monier et al., 2011)*

*The C&D waste is commonly collected and transported to the treatment facilities directly from the construction site by the contractor. The quality of the waste is influenced by the performance/specifications/requirements of selective demolition. The further processing generally includes only mechanical processing and further refining or utilization as material or as fuel in energy production. In all steps some rejects are generated.*

#### 3.1.2.2 C&I waste

C&I is often collected and treated, and usually reported together with MSW, which is why the future scenarios for C&I waste generation and treatment are reported together with the MSW. The average annual C&I generation is approximately 1 Mt. Figure 6 illustrates the material content of the C&I stream. Currently approximately 35% (350 000 tonnes) of the C&I stream is collected as mixed waste, and the content of the mixed waste is presented in Figure 7. Of the mixed waste, approximately 75% is landfilled, 7% is incinerated at mass incineration plants and the remainder is recycled and recovered as RDF.

C&I waste is very similar to MSW, but the fractions, especially plastics and metals, can be cleaner than the same fractions in MSW. The quantities of similar materials can also be larger than in MSW, which makes some of the fractions good for recycling. Especially metals, paper and cardboard are recycled, while the majority of the biowaste is landfilled. Figure 8 presents the results of the MFA analysis. (The data of the glass fraction is not very reliable, while the paper and cardboard is the most reliable of all fractions with several similar references.)

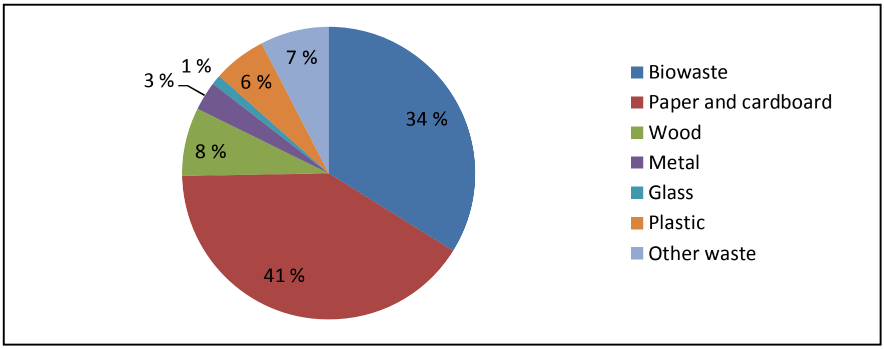



**Figure 6.** Composition of the C&I waste stream; others include C&D and hazardous waste.

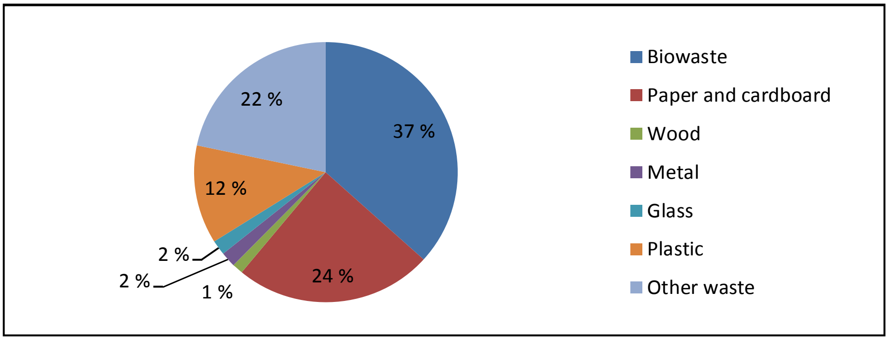



**Figure 7.** Composition of the C&I mixed waste; others include C&D and hazardous waste.

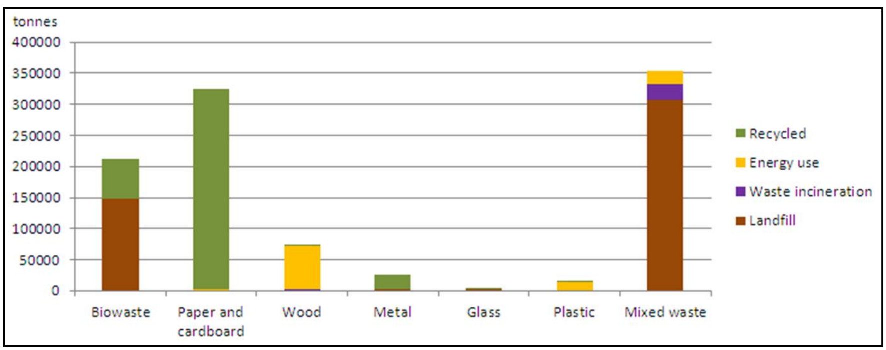



**Figure 8.** Results from the MFA analysis of C&I waste generation and treatment.

***Characteristics of C&I***

*The composition of commercial and industrial waste varies a great deal according to the origin of the waste. The main producers of C&I waste are offices, schools, restaurants, hotels, hospitals and retail stores. The main fractions of commercial waste are similar to those of municipal solid waste, but the shares of different fractions are different.*

*Different entities produce and recycle different fractions. Recyclables from C&I consist of plastics, paper, cardboard, metals, and glass, which are suitable for recycling and reuse. Plastics, paper and cardboard are also suitable for incineration but this is not a preferred option for handling waste according to EU waste hierarchy (Waste Framework Directive, 2008/98/EC). The waste which is not source-separated as pure material fraction ends up usually in mixed waste or is source-separated as energy fraction or biowaste.*

#### 3.1.2.3 MSW

The average annual MSW generation per capita in Finland is approximately 500 kg, of which the household waste makes up approximately 60% and the C&I the remaining 40%. In total approximately 2.5 Mt of MSW was generated in 2008 in Finland. Figure 9 illustrates the material content of the MSW stream (including C&I waste). However, currently approximately 60% of the MSW stream is collected as mixed waste, and the content of the mixed waste is presented in Figure 10.

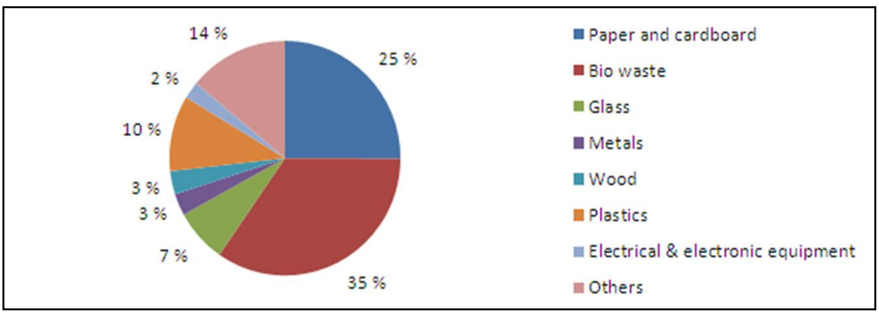



**Figure 9.** Composition of the MSW (including C&I) waste stream. Others include e.g. textiles and clothing, sanitary towels and nappies, mixed packaging, other combustible waste, other non-combustible waste, mixed waste (not packaging) and hazardous waste.

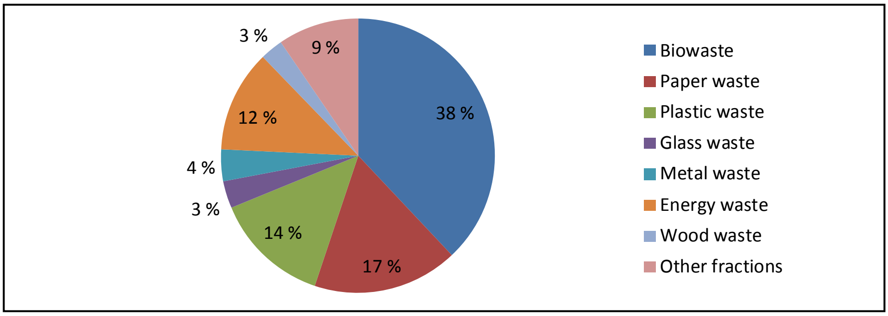



**Figure 10.** Content of the mixed MSW. Others include e.g. textiles and clothing, sanitary towels and nappies, mixed packaging, other combustible waste, other non-combustible waste, mixed waste (not packaging) and hazardous waste.

Figure 11 presents the results of the MFA analysis. MSW treatment in Finland is still based mainly on landfilling of mixed waste, although paper, glass and metals are rather efficiently separated and recycled. Biowaste separation is rather common and steadily increasing. In the past a decrease in landfilling and an increase in recycling and especially incineration have been seen.

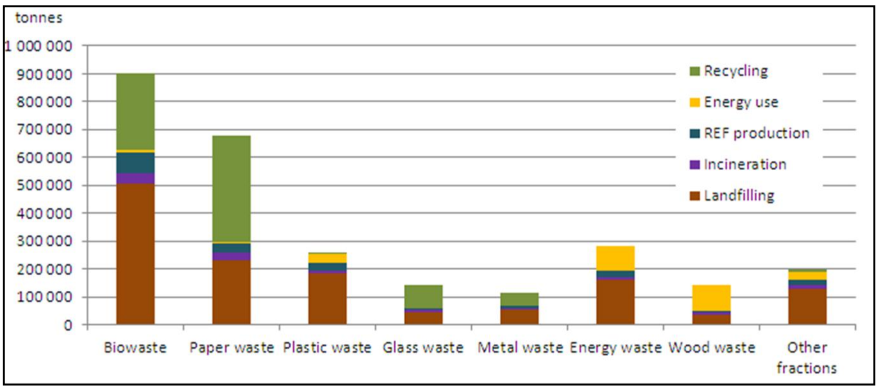



**Figure 11.** Results from the MFA analysis of MSW (including C&I) waste generation and treatment. Others include e.g. textiles and clothing, sanitary towels and nappies, mixed packaging, other combustible waste, other non-combustible waste, mixed waste (not packaging) and hazardous waste.

The MSW generation (including C&I) of a nation is commonly interconnected with its wealth; as a country develops, its waste generation increases, to slowly decrease when a certain level of prosperity is reached. In some of the European countries, indications of decoupling are already seen, and even in Finland it seems that the MSW amounts may be decreasing (Figure 12). The most significant changes in MSW composition result from the development of packaging materials and reduction in paper use. The share of plastics in MSW has been growing, and a further increase is expected. The market share of bio-based plastics will also slowly rise. The use of glass packages is expected to decrease due to substitution with plastics or other materials.

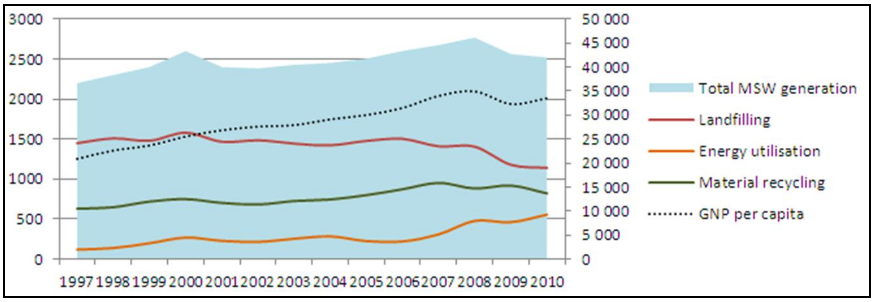



**Figure 12.** Development of MSW generation and treatment in Finland and the interconnection between MSW and GDP in Finland during the years 1997–2010 (Statistics Finland 2011a; 2011b).

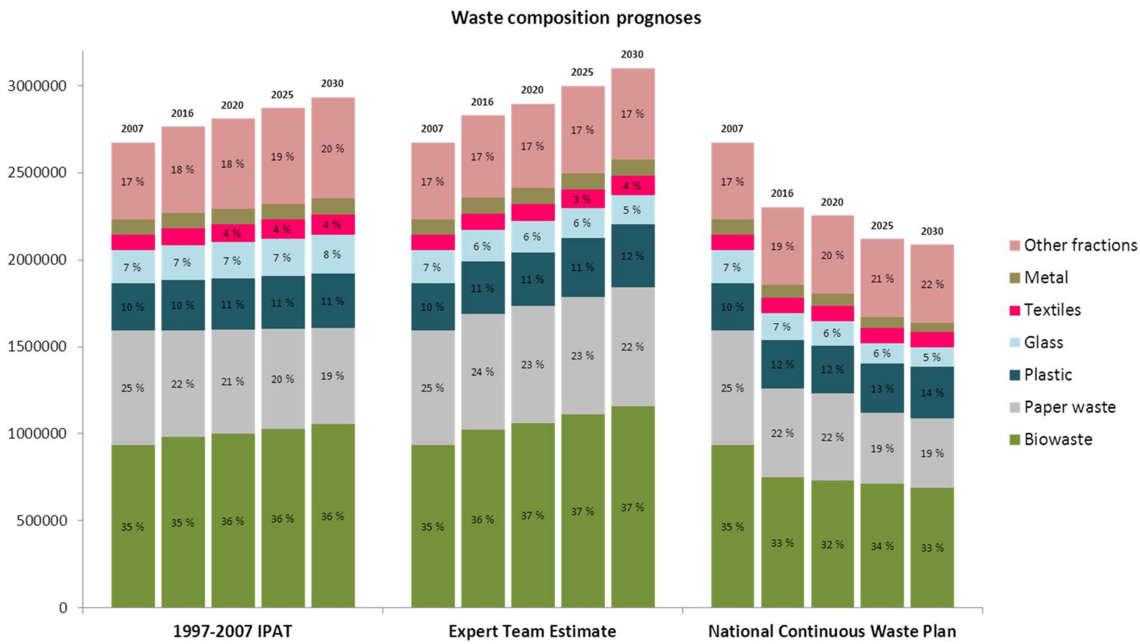



**Figure 13.** Three prognoses for MSW stream composition changes by the year 2030 (based on Moliis et al., 2009)

Figure 13 presents the estimates of composition changes from three different forecast methods. Three different MFA scenarios were modelled; both quantity and composition changes has been considered in the modelling. Only changes compared with the current state have been made on the quantities and composition, none with efficiencies. In addition, the models were run to estimate the situation in 2020. In Table 6 the compositions and quantities of MSW (including C&I) scenarios and current state are presented.

- 1997–2007 IPAT[1] (Moliis et al., 2009). The 1997–2007 IPAT which simply follows the trend measured shows a slight increase in total waste (+10%) with paper waste being the only diminishing fraction (-16%). Sorting is estimated to remain as efficient as it is in the current state. Cardboard and paper fraction is assumed to distribute similarly as in the current model (appr. 70% paper, appr. 30% cardboard). REF and energy use streams are higher in Scenario 1 than in the current model, since they also include the wood fraction.
- Expert Team Estimate. The Expert Team Estimate shows a more rapid growth (+ 16%) with biowaste (+ 24%) and plastics (+32%) growing rapidly and glass being the only diminishing fraction (-10%). The model of Scenario 2 is similar to Scenario 1 except for the sorting distribution which is different due the differing composition of the waste.
- The Finnish National waste plan has set a goal of cutting MSW production to the year 2000 level by 2016. The National Continuous Waste Plan expects all fractions except plastics (+ 7%) to diminish rapidly (-22% total waste decrease). The model is otherwise the same as in previous scenarios except for the sorting distribution. In addition, the entire waste quantity is significantly smaller than in previous scenarios.

**Table 6.** Estimated compositions and quantities for 2020 based on three scenarios and the current situation.

| | Current (2008) | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|---|
| MSW t/a | 2 706 646 | 2 811 000 | 2 897 000 | 2 255 000 |
| Metals % | 4 | 3 | 3 | 3 |
| Glass % | 5 | 7 | 6 | 6 |
| Paper % | 25 | 21 | 23 | 22 |
| Organic waste % | 33 | 36 | 37 | 32 |
| Other % | 33 | 33 | 31 | 37 |

[1] IPAT is a simple forecast model based on the following equation: I = P*A*T, where I = population, A = GDP and T = Technology level factor, here MSW/BKT. In 1997–2007 IPAT T is based on development between years 1997–2007.

In Figure 14, a comparison of the quantities for different utilizations and losses (exhaust gases from composting) as well as landfilling are presented for the current state and three scenarios. The MSW quantity produced will increase in Scenario 1 and 2, while in Scenario 3 the quantity will decrease compared with the current state. Approximately 1.55 Mt/a of MSW will be landfilled in future (Scenarios 1 and 2) if the efficiencies of the processes do not change. Based on the estimation of the National Continuous Plan (Scenario 3), the landfilled MSW amount would decrease to 1,2 Mt/a from current 1,47 Mt/a. The quantity of MSW directed for material utilization would be between 430 kt/a and 550 kt/a. Energy utilization and incineration would together be between 440 kt/a and 540 kt/a.

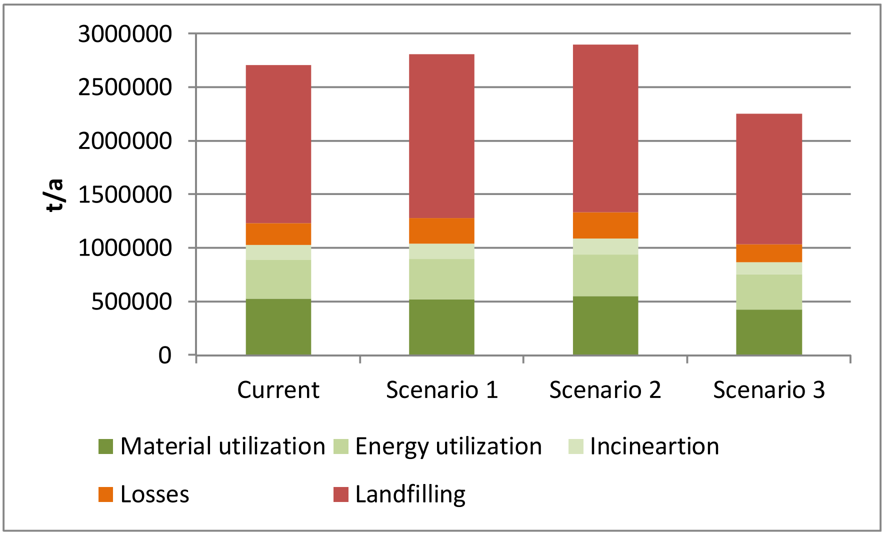



**Figure 14.** Utilization, loss and landfilling quantities for different scenarios.

Since the separation and sorting efficiencies are not changed, the utilization rates are in the same category as in the current situation. Some small differences can be noticed in the rates, since the MSW composition is slightly different in each scenario. Utilization rates and shares of losses as well as landfilling are presented in Figure 15. The composition and quantity changes seem not to have a major effect on the utilization rates; the results of Scenarios 1 and 2 in particular are rather similar. The only noticeable difference between these scenarios is the higher material utilization rate in Scenario 2, which may be caused by the higher paper share in the MSW composition. Scenario 3 differs more from the previous scenarios both in composition and results. The higher energy utilization may be caused by a greater share of "other" fractions, which have higher energy utilization rates than the other waste fractions. In addition, a smaller share of losses in Scenario 3 is probably caused by a smaller proportion of organic waste in the MSW composition.

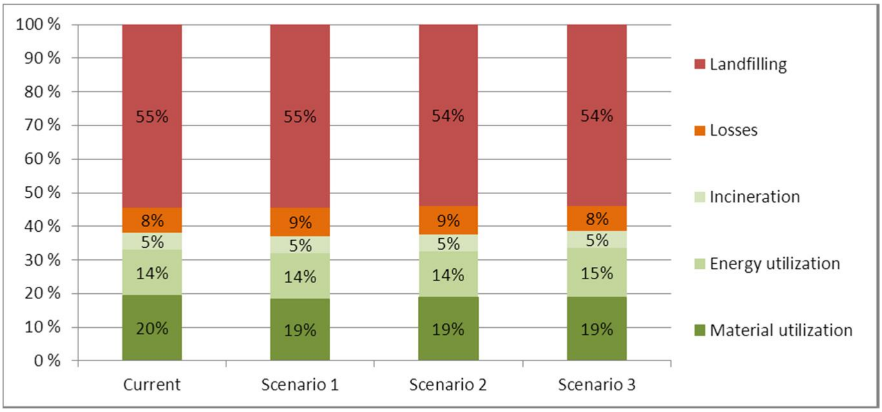



**Figure 15.** Utilization efficiencies, loss and landfill shares.

***Characteristics of MSW***

*A typical feature of MSW is that it is continuously generated, and its characteristics are similar regardless of the generation site. MSW treatment consists of seven individual process chains for the separate waste fractions (mixed (including plastics), metals, glass, paper, cardboard, bio, wood and REF/energy). These fractions can be partly mixed together or separated, depending on the waste management system. Sorting is assumed to be done in households or at sorting stations.*

*The MSW management chain consists of three main steps: generation (including collection and transport), processing (including disposal), as well as utilisation of the recycled materials. The MSW produced has to be collected (possible separate collection) and stored before transport to further processing or final disposal. The further processing generally includes mechanical and/or biological processing and further refining or utilization as material or as fuel in energy production. In all steps some rejects are generated.*

### 3.1.2.4 WEEE

The WEEE stream is commonly divided based not on materials but on the categories defined in the WEEE-directive (EU, 2003). Figure 16 illustrates the breakdown into the categories of WEEE for the generated WEEE before separation into the reuse/storage and collection streams.

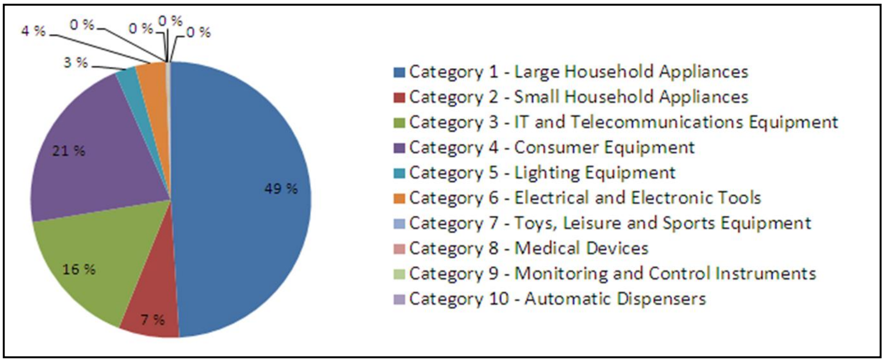



**Figure 16.** Breakdown of average arising WEEE categories in 2005 (United Nations University, 2007). The breakdown of the WEEE entering the waste stream will differ from this due to different collection rates of the different categories.

The collection of WEEE in Finland was approximately 54 kt in 2008 (Eurostat, 2008). Figure 17 illustrates an estimation of the material content of the collected WEEE. The utilisation rate of the WEEE stream is quite high, as can be seen in Figure 18. The Finnish legislation recommends reuse before recycling for all waste, but only a very small amount of the collected WEEE is reused. In reality the rate of WEEE reuse is higher, due to devices handed on to relatives or friends when purchasing new ones; another common alternative is to store old appliances in case of later need instead of discarding as waste. Also a part of the WEEE is collected with the mixed waste. These reused/stored items do not enter the WEEE waste stream, and therefore is not part of the statistics for collected WEEE. However, this alone cannot explain the high rate of WEEE missing from the statistics. (Ignatius et al., 2009.)

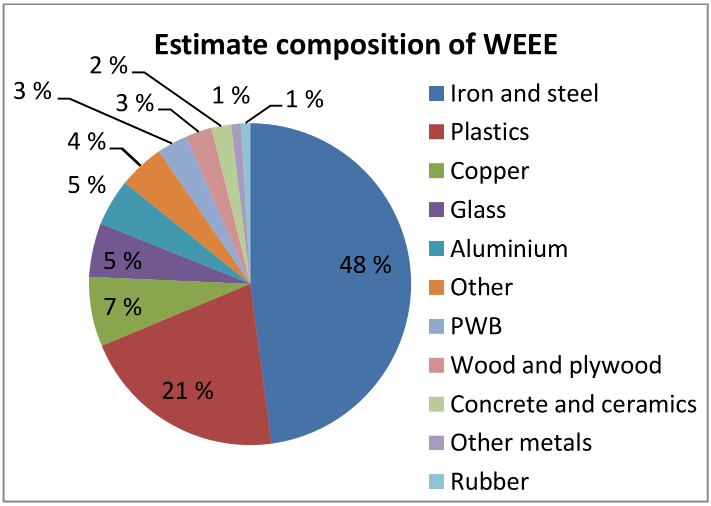



**Figure 17.** Composition of the collected WEEE (United Nations University, 2007).

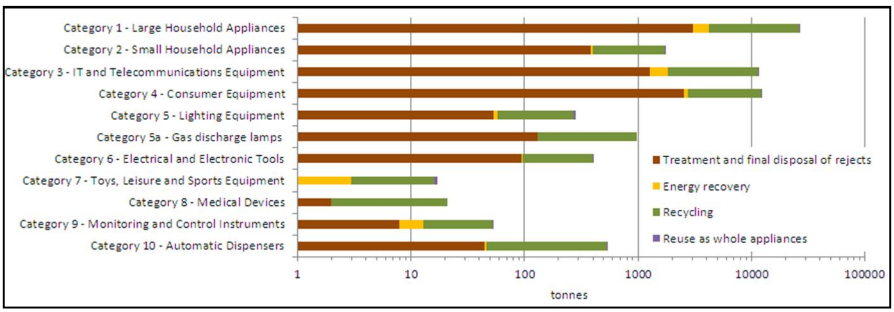



**Figure 18.** Assessment of the treatment of WEEE; note the logarithmic scale (Eurostat, 2008). (The results of the MFA analysis of the WEEE chain will be published in a separate report.)

In this research the focus is on the material value of the waste, and two groups of devices are examined: high and low value WEEE products. Low value WEEE products are composed mainly of small household appliances, such as vacuum cleaners, toasters or coffee machines (devices with a lot of plastic parts and only a small amount of valuable materials). High value WEEE products compose mainly of metals, plastics, printed circuit boards, cables and wires, power supplies, DVD and CD stations, hard drives and batteries. Most of the value in high value products lies in the printed circuit boards. The material contents of two examples representing high and low value WEEE are presented in Figure 19.

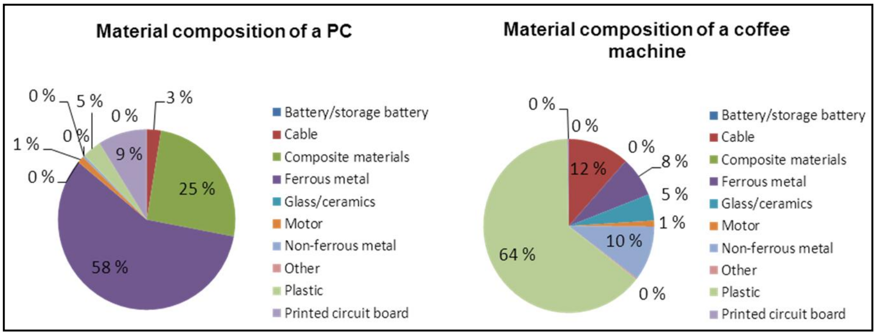



**Figure 19.** Two examples of the composition of low and high value WEEE, to the left a PC represents high value and to the right a coffee machine represents low value WEEE (Chancerel & Rotter, 2009).

The hazardous substances of WEEE include heavy metals (e.g. lead, mercury, cadmium, chromium), PCB, flame retardants among others (Ogilvie, 2004). Storing WEEE outside exposes equipment to wear and sun radiation and enables, for example, phthalates and brominated flame retardants (BRFs) to migrate to the environment producing the risk of soil contamination. In separation and shredder processes, heavy metals and BRFs can be released but also dioxin formation can occur due to heat and high pressures developed in the processes. There is also a risk of the emission of ozone-depleting substances through improper handling of cooling and freezing appliances. In the incineration process, some environmentally hazardous organic substances (e.g. BFRs) are converted into less hazardous compounds, but there is a risk of emission of dioxins as well as a risk of volatile heavy metals and their oxides. (Crowe et al., 2003)

Waste electrical and electronic equipment consists of a large amount and variety of recyclable materials. The concentrations of most valuable materials are very small and becoming even smaller. In the future, more electronics will be found in other sources than consumer appliances, including end-of-life vehicles, demolished buildings, infra networks, etc. The consumption of critical metals in energy applications, such as permanent magnets, solar panels, etc. is expected to grow considerably.

The amount of waste electrical and electronic equipment, WEEE, is probably the fastest growing waste stream in the EU. The amount is expected to grow from 8.3–9.1 million tonnes in 2005 and to roughly 12.3 million tonnes by 2020. Both the numbers of electrical and electronic devices put on the market as well as the amounts collected are growing steadily, as is shown in Figure 20. The lifespan of different products as well as for the different categories varies. I.e. for computer products the average time in use is 5–6 years (EuP, 2007). The expectation of a growing amount of WEEE in the future is based on the growth on electrical and electronic equipment put on market (at present) in combination with the expected lifespan of each product. This explains the fact that the amounts put on the market are much larger than the amounts collected. (Eurostat, 2008)

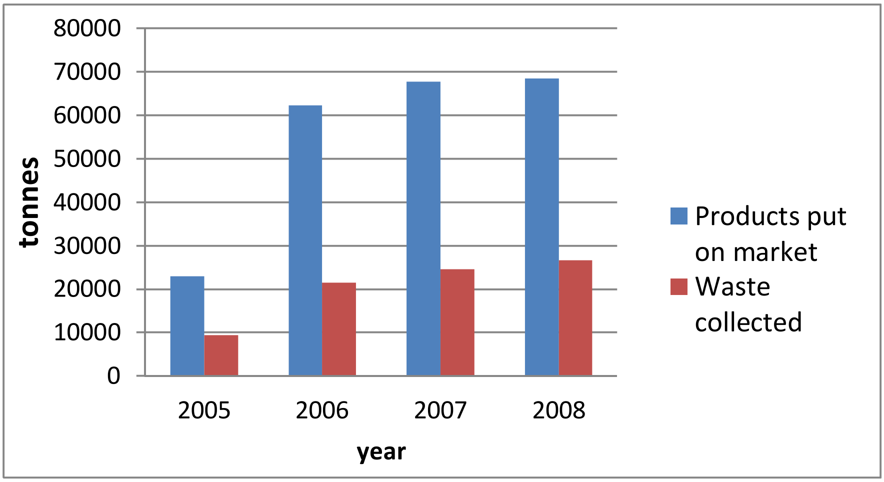



**Figure 20.** EEE and WEEE put on the market and collected in Finland, development 2005–2008 (Eurostat, 2008).

***Characteristics of WEEE***

*Waste electrical and electronic equipment originates from households and industry. WEEE is a very versatile waste fraction and includes a vast variety of different items. WEEE items are divided into 10 categories, with several items in each category. (Directive 2002/96/EC) These categories are defined by the type of product or the intended use of the product, and not by the type of material composition of the items or similar treatment options, which would be more logical from a waste management viewpoint.*

*Waste electrical and electronic equipment consist of a large number and variety of recyclable materials, some of which are valuable, as well as a considerable variety of hazardous materials (Törn et al., 2010). Typical materials are various metals, plastics, composite materials, and glass. The most valuable components contain metals with a high market value, while some items mainly consist of plastic which can be used for energy recovery (United Nations University, 2007). The hazardous substances of WEEE include heavy metals, PCB and flame retardants among others (Ogilvie, 2004).*

#### 3.1.2.5 ELV

The End-of-Life vehicle (ELV) waste generation in Finland was approximately 64 kt in 2011 (Data source: Finnish Car Recycling, 2012a). Figure 21 illustrates the material content of the ELV stream. Currently, mainly the metals (75%) are recovered as raw materials, the remaining 25% which is called Automotive Shredder

Residue (ASR or SR) or car fluff, is in Europe classified as hazardous waste (Vermeulen et al., 2011). ASR is made of plastic (19–31%), rubber (20%), textiles and fibre materials (10–42%) and wood (2–5%), which are contaminated with metals (8%), oils (5%), and other substances, some of which may be hazardous (about 10%), e.g. PCB, cadmium and lead. (Nourreddine, 2007) The standard method of ASR disposal has been landfilling, now limited by the stringent legislation and the objectives/legislation related to ELV treatment of various countries and imposes an increased efficiency on the recovery and recycling of ELVs.

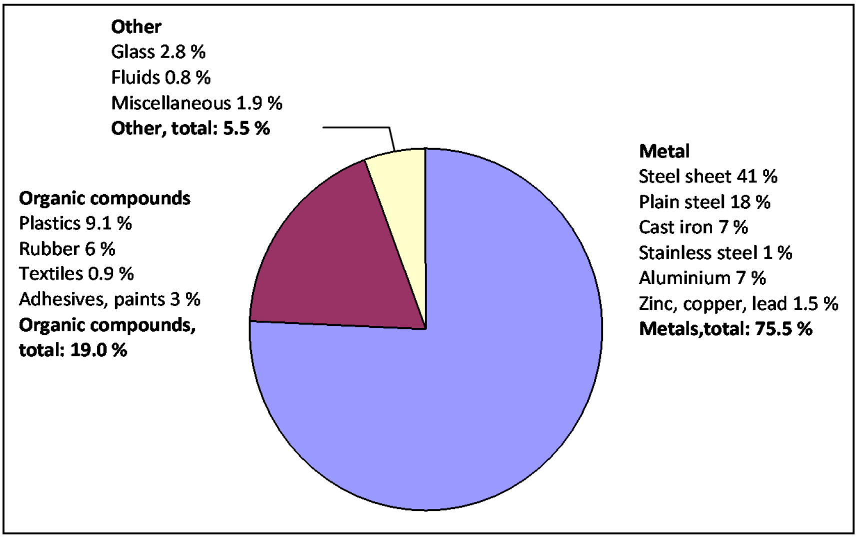



**Figure 21.** Average material content of ELV (data source: Finnish Car Recycling, 2012b).

On a new vehicle, for which component parts, materials or both can be taken into account, the calculation of the recyclability and recoverability rates are carried out through four main steps: depollution, dismantling, metals separation and non-metallic residue treatment (ISO 22628:2002). Depollution concerns about 3% in weight of ELV materials; it consists of the removal of batteries, fluids, heavy metals containing components, or potentially explosive elements (e.g. airbags) (Morselli et al., 2010). During dismantling, parts and materials are removed for recovery. The materials removed at this stage range from 9% for old (natural) ELVs to 47% for new (premature, e.g. damaged) (Morselli et al. 2010). The treatment of the recovered materials of the dismantling process is illustrated in Figure 22. The remaining materials are shredded, after which materials are separated, based on physical and optical properties. The residue (ASR) consists of approximately 25% of the ELV mass, which is partly incinerated and partly landfilled. The treatment of the materials in the shredding process is illustrated in Figure 23.

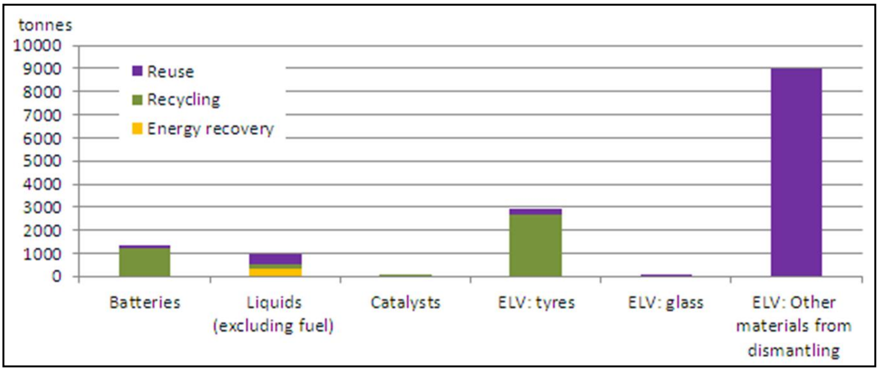



**Figure 22.** Assessment of the materials recovered at the dismantling and depollution stage (European Commission, 2012d) (The results of the MFA analysis of the ELV chain will be published in a separate report).

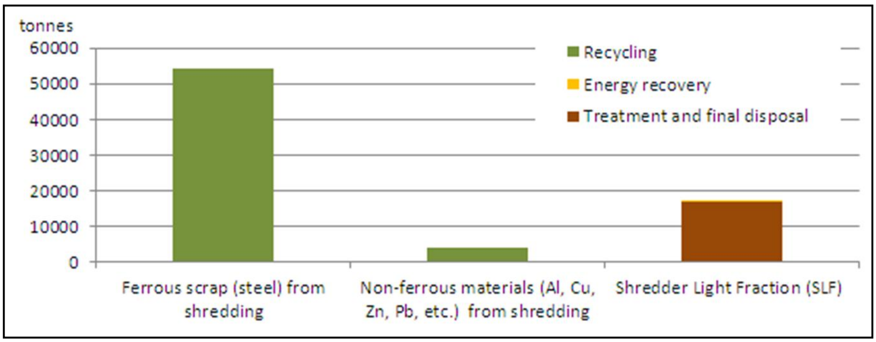



**Figure 23.** Assessment of the recovered materials from the shredding process (European Commission, 2012e). (The results of the MFA analysis of the ELV chain will be published in a separate report.)

Every year, ELVs generate between 8 and 9 million tons of waste in the EU (European Commission, 2012a). In 2007 about 73 million vehicles were produced worldwide. Compared to about 38 million vehicles produced in 1980, the worldwide production for cars is growing steadily (Vermeulen et al., 2011). The projection in Figure 24 shows that the number of ELVs for the EU25 will probably increase by 45% between 2005 and 2030. Taking into account the mass of export of used cars, which is about 2 million, it can be expected that by 2030 the total mass of ELVs generated per year in the EU25 will reach 14–17 million tonnes. (Vermeulen et al., 2011.)

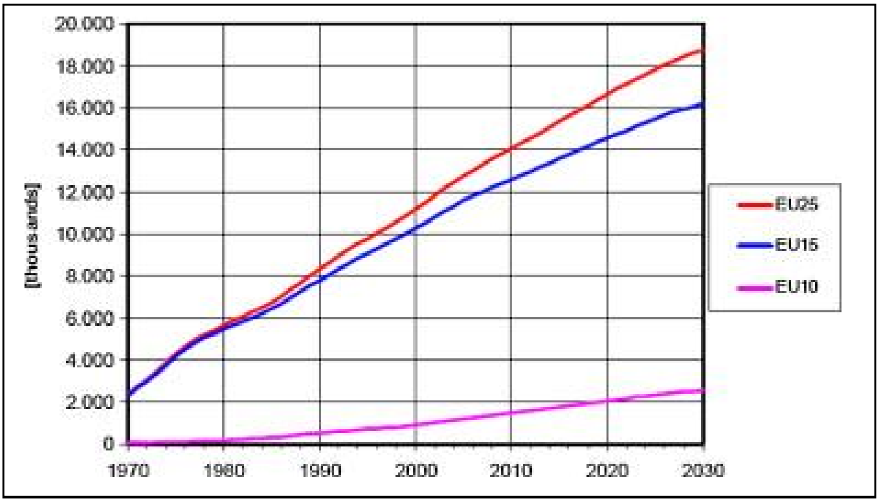



**Figure 24.** Projected number of End-of-Life vehicles in the period 2005–2030 for the EU member states without Romania and Bulgaria (EU25), for the older EU countries (EU15) and for the new EU countries (EU10) (Vermeulen et al., 2011)

In the future, based on changes already made in vehicle design in order to reduce the environmental impact of cars and to increase sustainability, both the weight and composition of ELV will change. The average weight of ELVs will increase, and the share of an ELV by weight accounted for by plastics will increase while the share accounted for by ferrous metals (mainly steel) will decline. However, the absolute weight of metals will increase. (European Commission, 2006a)

ASR recovery: Under evaluation by both car producer and recycling companies at this time, great innovations are expected in the next few years, i.e. concerning material separation enhancement, thermo-chemical conversion (gasification and pyrolysis) and recycling/recovery routes of the residue (Vermeulen et al., 2011). Possible upgrading by secondary recovery techniques can produce a fuel- or filler grade ASR (the application in waste-to-energy plants, in cement kilns or in metal-lurgical processes is possible with limitations). The ASR quantities are likely to increase in the coming years due to the growing number of cars being scrapped and the increase in the amount of plastics used in car production. (Morselli et al., 2010.)

***Characteristics of ELVs***

*It has been estimated that the number of deregistrations in the EU25 is about 12.6 million in every year of which about 3 million are exported (about 2 million are exported to another member state and about 1 million are exported outside the EU) (European Commission, 2006a). In 2011 in Finland 64 851 certificates of destruction (CODs) were issued (54 634 CODs in 2010) (Finnish Car Recycling, 2012a). However, in many member states including Finland, the number of ELVs represents less than 50% of the number of deregistered cars (Schneider et al., 2010). Thus there is a clear lack of detailed information about the further use of more than 50% of the deregistered cars, and also a clear need for improvements of data quality and availability of national vehicle markets.*

*As a result of the strict legislation related to ELV treatment of various countries, the requirements for the treatment and disposal of ELV is becoming more challenging (Vermeulen et al., 2011). From old vehicles, component can be reused and materials recycled through four main steps: Depollution, Dismantling, Metals separation and Non-metallic residue treatment. Dismantling is the removal of valuable parts and materials which can be re-used or recycled (e.g. glass, metallic components containing aluminium, magnesium, copper, rubber and plastic elements).*

*Ferrous metals, which are mainly composed of iron and have magnetic properties, are the main component of ELV. Ferrous metals are removed from ELV by a series of mechanical and magnetic processes.*

*Non-ferrous metals, such as aluminium, copper, lead, zinc, and nickel, are in general removed from ELVs by eddy current or dense media separation.*

*The remaining materials constitute the non-metallic residue, also called ASR or car fluff (approx. 25 % of the ELV). Light fraction fluff, size > 30 mm, represents about 50 % of the total ASR or SR stream (approximately 25% of an ELV). Considering only the coarse and oversize fraction, typically 40% (i.e. 20 % of total ASR or 5% of an ELV) of it can potentially be recovered (Forton et al., 2006; Redin et. al., 2010).*

### 3.1.3 Current utilisation and losses of material potential in the selected waste chains

The current waste generation of the waste chains presented in this report is presented in Table 5. The material potential of the waste chains is the currently generated waste and the losses (the non-utilised waste volumes). In order to utilise the whole potential, improvements need to be made. Of course, a complete 100% recycling rate is never possible, but it is safe to estimate increasing recycling rates in the future. With increasing raw material prices, the economic feasibility of recycling can improve, thus, creating an increased demand for recovered materials. With improving technology solutions the supply of recovered raw materials can also grow, meeting the increasing demand.

**Table 7.** Current waste potential of the selected waste chains.

| | C&D* | MSW** | C&I*** | WEEE**** | ELV***** |
|---|---|---|---|---|---|
| Mixed, t/a | | | | | 1 300 |
| Plastic, t/a | * | 221 000 | 59 000 | 11 500 | 5 800 |
| Glass, t/a | * | 187 000 | 10 000 | 2 700 | 1 900 |
| Metals, t/a | 270 000 | 48 000 | 33 000 | 33 000 | 48 600 |
| Wood, t/a | 720 000 | 7 100 | 78 700 | 1 600 | |
| Paper & cardboard, t/a | | 248 000 | 423 000 | | |
| Biowaste, t/a | | 570 000 | 354 000 | | |
| Aggregates, t/a | 700 000 | | | 1 100 | |
| Others, t/a | 310 000 | 365 000 | 71 000 | 4 400 | 6 400 |
| **Total, t/a** | **2 000 000** | **1 647 000** | **1 028 000** | **55 000** | **64 000** |

*others include e.g. gypsum, glass, plastic, packaging, mixed wasta and hazardous waste
** for MSW domestic (ei.e C&I excluded) composition of the waste, others inlude e.g. textiles, sanitary towels and nappers, mixed packaging, other combustible waste, other non-combustible waste, mixed waste and hazardous waste
*** for C&I waste stream others include e.g.hazardous and C&D waste
**** for composition of WEEE collected
***** others include rubber, textiles, paints & fluids

From the economic and usually also sustainability point of view, it is important to exploit the synergies between various waste streams, e.g. by an integrated treatment and utilization of similar or complementing waste fractions. As can be seen from Table 8, waste fractions, such as metals, plastics and glass are present in all the waste streams analysed. For planning of material use, this general classification is too simplified, because the categories comprise different types of materials with different properties.

The next level is to find out what are the individual shares of different material types in the target streams. As an indicative estimate of the composition of plastic waste, the European level percentages of the most common plastic types in the selected chains and in packaging waste are presented in Table 6 (Delgado et al., 2007). Apart from the situation in 2005, a development scenario for 2015 was made by the authors. The packaging plastics category overlaps with other categories, especially MSW, where the estimated share of packaging plastics is 60–80% of all the plastics contained.

**Table 8.** The percentages of most common plastic types (% in each plastic waste stream) in selected waste streams in the 2005 and 2017 scenarios (Delgado et al., 2007).

| **2005 scenario, wt-% in plastic waste streams** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | HDPE | LDPE | PET | PP | PS | PU | ABS | PVC | PA |
| Packaging | 17-22 | 30-35 | 12-17 | 17-20 | 10 | | | 4 | |
| MSW | 15-20 | 38-43 | 7-12 | 5-10 | 12-17 | | | | |
| C&D | 4-9 | | | | 14-19 | 3-8 | | 50-55 | |
| WEEE | | | | 7-12 | 26-31 | 13-18 | 27-30 | | |
| ELV | 3-8 | | | 28-33 | | 8-13 | 12-17 | 5-10 | 4-9 |
| Agriculture | | 60-65 | | 2-5 | | | | 18-23 | |
| **2017 scenario, wt-% in plastic waste streams** | | | | | | | | | |
| | HDPE | LDPE | PET | PP | PS | PU | ABS | PVC | PA |
| Packaging | 22-27 | 30-35 | 20-25 | 15-20 | 9 | | | 2 | |
| MSW | 15-20 | 38-43 | 12-17 | 5-10 | 12-17 | | | | |
| C&D | 4-9 | | | | 18-23 | 7-12 | | 45-50 | |
| WEEE | | | | 17-22 | 20-25 | 6-11 | 18-23 | | |
| ELV | 7-12 | | | 38-43 | | 8-13 | 5-10 | 5-10 | 6-11 |
| Agriculture | | 60-65 | | 2-5 | | | | 18-23 | |

Besides polymer composition there are other barriers to the integrated material use of plastics, such as contamination of the plastics, e.g. various residues in packages; various potentially hazardous additives, such as flame retardants, metal pigments and blowing agents, and an increasing use of composite packages.

#### 3.1.3.1 C&D waste

The material potential of the C&D waste chain is presented in Figure 25. The low recycling rate for wood is due to its cheaper and easier energy recovery. Wood is an abundant renewable resource in Finland, which is also used as virgin for energy recovery. But there are a few applications for material recycling, which is why from an economic point of view energy recovery can be seen as equal to recycling. Of the metals approximately 75% are sorted for recycling, but metals separated from the other waste streams allow approximately 91% of the C&D waste metals to be recovered. Others include e.g. plastics, glass, insulation and gypsum originating from mixed waste, and only 50% of these are sorted for REF production. After treatment, approximately 38% of the C&D stream is recycled as material, 35% is recovered as energy, 6% is utilized at landfills and 21% is landfilled; thus the losses can be seen as either only the landfilled volume or also the volume utilised at landfills as well. In order to improve the material utilisation of C&D waste, the identification and sorting technologies should be improved, as also the on-site sorting rates.

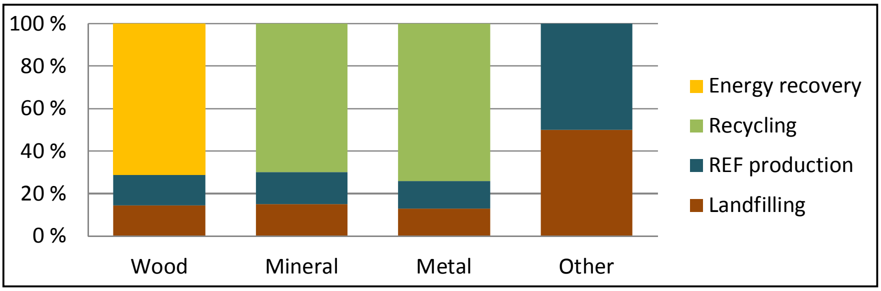



**Figure 25.** Results from the MFA analysis of C&D waste generation and treatment of utilised and remaining material potential of the C&D waste chain. Others include e.g. gypsum, glass, plastic, packaging, mixed waste and hazardous waste.

### 3.1.3.2 C&I waste

The estimated material potential of the C&I waste chain is presented in Figure 26. Currently approximately 46% of the waste is recycled and 11% utilised in energy production, the remaining 41% is incinerated in mass burning plants and 3% landfilled. 87% of the current material potential is being utilised. Currently approximately 35% of the C&I stream is collected as mixed waste; of the mixed waste approximately 75% is landfilled, 7% is incinerated at mass incineration plants, and the remainder is recycled and recovered as RDF. Thus, the majority of the loss in utilised material potential originates from mixed waste collection. (The data on the glass fraction is not very reliable, while the paper and cardboard is the most reliable of all fractions with several references.)

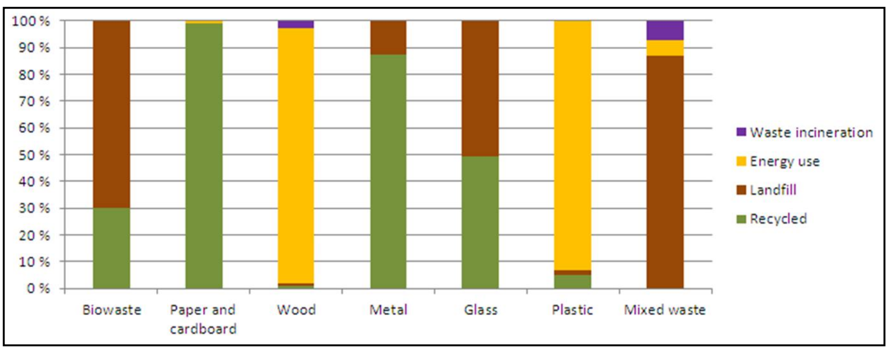



**Figure 26.** Results from the MFA analysis of C&I waste generation and treatment of utilised and remaining material potential of the C&I waste chain.

### 3.1.3.3 MSW

The material potential of the MSW waste chain is presented in Figure 27. Currently approximately 30% of the waste is recycled, 9% is utilised in energy production and 7% is utilised for REF production. The remaining 5% is incinerated in mass burning plants and 49% is landfilled. Thus, less than 50% of the current material potential is being utilised. If not suitable for recycling, the source-separated waste is also used for energy recovery or REF production; the efficiency of material recovery of e.g. plastics and wood is dependent on the cleanliness and homogeneity of the fractions, which commonly is quite poor for MSW.

Currently only 40% of the MSW is site-sorted; the majority of the site-sorted waste is recycled (only approximately 2% is incinerated or landfilled). Thus, the high landfilling rate is mainly due to the lack of site-sorting. However, current site-sorting efficiencies are not sufficient to cover the increasing sorting demand, which is why alternative sorting technologies may prove efficient. Metals, as well as paper and cardboard, have quite a high value as recovered raw materials, why the sorting should be intensified in order to increase the recovery rates.

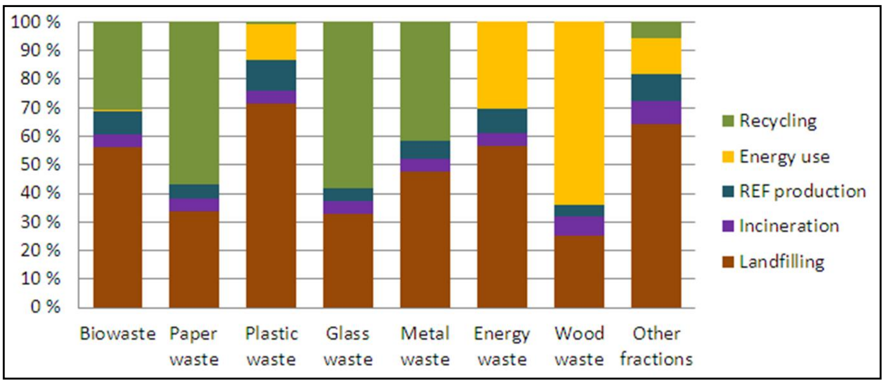



**Figure 27.** Results from the MFA analysis of MSW waste generation and treatment of utilised and remaining material potential of the MSW waste chain. C&I is included in the MSW chain due to lack comparable data on the separate streams. Others include e.g. textiles and clothing, sanitary towels and nappies, mixed packaging, other combustible waste, other non-combustible waste, mixed waste (not packaging) and hazardous waste.

### 3.1.3.4 WEEE

WEEE has an 85% recovery rate and an 82% recycling rate of the collected waste. Even though legislation recommends reuse before recycling, only a very small amount of the WEEE is collected for reuse purposes. A significant part of the end-of-life electrical and electronic equipment never enters the intended collection system as illustrated in Figure 28; since the majority of the collected waste is recovered, emphasis should be on recovering this missing part of the waste stream.

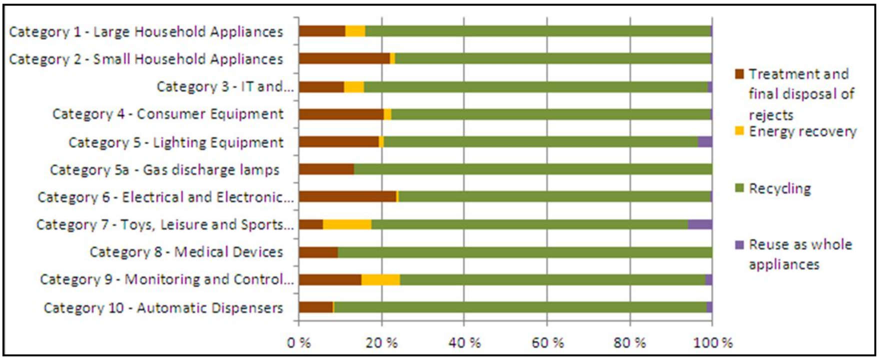



**Figure 28.** Reported generation and treatment of utilised and remaining material potential of the WEEE categories (Eurostat, 2008). (The results of the MFA analysis of the WEEE chain will be published in a separate report.)

3.1.3.5 ELV

ELV Reuse and Recycling rate, 2009 in Finland were 81% (European Commission, 2012f). The main treatment processes of materials are dismantling and shredding, where some materials are recovered even at the dismantling stage, as illustrated in Figure 29, and the remainder are shredded and separated for treatment, as illustrated in Figure 30.

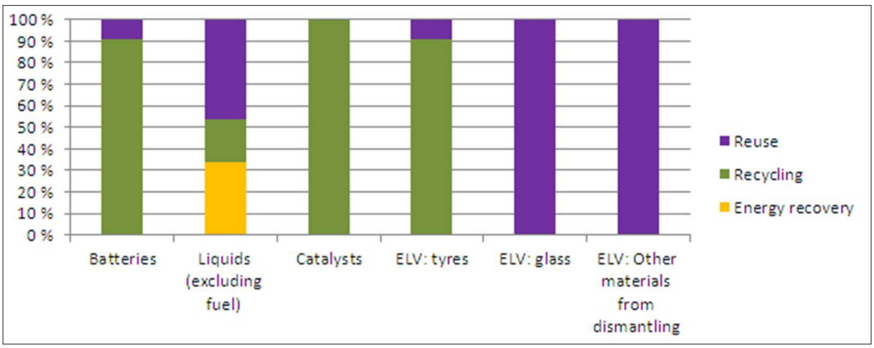



**Figure 29.** Assessment of the utilisation and remaining material potential of the recovered materials from dismantling (European Commission, 2012d). (The results of the MFA analysis of the ELV chain will be published in a separate report.)

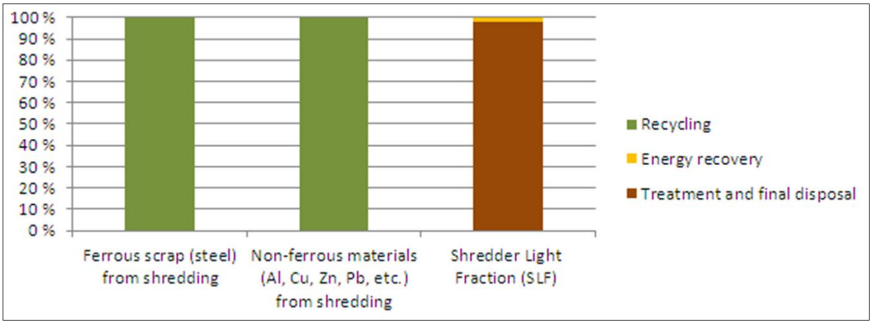



**Figure 30.** Assessment the utilisation and remaining material potential of the recovered materials from the shredding process (European Commission, 2012e). (The results of the MFA analysis of the ELV chain will be published in a separate report.)

#### 3.1.3.6 Increasing the utilisation rate

As can be seen FOR C&D, MSW and C&I, the main obstacle to increased utilisation of the material potential is the collection of mixed waste instead of site-sorting, and the inefficient mechanical sorting of the mixed waste. Enabling more efficient site and mechanical sorting of the waste would generate cleaner fractions for recovery. Site-sorting can only reach a certain efficiency due to people's lack of interest in and knowledge of materials. Also, increased site-sorting generates increased transport costs, which again reduces the economic incentive to recycle. Thus, although site-sorting should increase, the mechanical sorting technologies should be developed and utilised to reach the material potential of the waste generation.

***Sorting and separation***

*Recycling requires the waste fractions to be thoroughly separated either as on-site sorting or in mechanical sorting facilities. In most cases the sorted waste fractions require some kind of processing to recover economically profitable materials. Sorting is based on different identification methods and combinations of these, such as magnetic properties, density, size, and optical properties. There are two alternative sorting methods; on-site sorting and mechanical sorting:*

*In on-site sorting, waste is sorted before collection and transportation; e.g. sorting at home, in construction sites, or in offices. On-site sorting reduces the need for sorting appliances at waste treatment facilities, reducing the waste treatment costs. Furthermore, the waste fractions are never in contact with each other, reducing the risk for contamination, and improving the quality and recycling rate of all fractions. On-site sorting, however, increases the number of waste fractions, and consequently the need for collection containers and infrastructure, thus increasing collection costs. Of the waste streams studied in this project, C&D, MSW and C&I can be sorted on site.*

*Mechanical waste separation reduces the number of waste fractions and required infrastructure, thus reducing the cost and efforts associated to on-site sorting. However, when mechanically separated, the material is not as clean as it would be when source-separated. The mixed waste is commonly separated in a series of mechanical processes which identify different materials based on their mechanical properties. Of the waste streams studied in this project, WEEE and ELV consist of bulky heterogeneous materials, which can only be separated mechanically, but they must first undergo size reduction in order to enable the material separation.*

### 3.1.4 Energy recovery

The total amounts, current waste-to-energy (WTE) and potential for WTE of the waste chains examined are presented in Table 9. The total potential for incineration is calculated based on suitable fractions for WTE coming from waste chains. MSW includes also C&I, but the amounts of C&I waste are also presented separately from MSW. The fluff coming from ELV processing seems to be least utilized, since 98% of it is not utilized in WTE. However, clearly the largest potential is in MSW, where an annual additional 2 200 kt could be used for WTE and material recycling. Since the C&I waste is also included in MSW, this means that MSW accounts for 86% of total potential for WTE and material recycling from these waste chains.

**Table 9.** Total potential and utilized amounts of WTE in Finland.

| | Total amount | Total potential for WTE | | Current WTE | |
|---|---|---|---|---|---|
| | kt/a | kt/a | GWh/a | kt/a | GWh/a |
| WEEE [a] | 55 | 11 | 85 | 2 | 11 |
| C&D [b] | 2 000 | 890 | 3 700 | 570 | 2 400 |
| C&I [a] | 1 100–1 700 | 1 100–1 700 | 4 500–7 100 | 400 | 1 700 |
| MSW [a] | 2 700 | 2 700 | 7 500 | 510 | 1 900 |
| ELV [c] | 110–130 | 18–21 | 420–500 | 0,41 | 2 |
| [a]2008 [b]2010 [c]2009 | | | | | |

#### 3.1.4.1 Future prospects for WTE

The energy recovery of C&D waste is limited by the directive 2008/98/EC (EU, 2008), which sets a 70% target by 2020 for material recovery from non-hazardous C&D waste (i.e. not including CCA impregnated wood waste). Wood comprises 35% of C&D waste in Finland, of which the majority is used in energy utilization. As part of the mixed C&D is also recovered as energy, the total energy recovery rate is already 35%, exceeding the target of the directive. Thus, the C&D energy recovery should not be increased if one is aiming to reach the target of the directive.

Municipal solid waste can be incinerated in several combustion systems including travelling grate, rotary kilns, and fluidised beds. Increased bed temperature, combustion control and oxygen addition can be used in grate firing (SYNCOM+ process) (Martin Gmbh, 2011). Gasification and pyrolysis are quite often mentioned as the future WTE solution. C-Tech Innovation (2003) stated that the major advantage of pyrolysis and gasification is high-efficiency electricity generation with CCGT (combined cycle gas turbine). One disadvantage of gasification as against grate firing can be the costs, because CCGT plant is quite expensive.

Commercial and industrial waste has better quality than municipal solid waste in general. However, C&I waste availability for incineration can be lower than that of MSW since it contains more materials suitable for recovery and recycling (World Bank, 1999). Due to better quality, commercial waste is more suitable for SRF production and waste combustion facilities using fluidized bed boilers, than MSW. The gasification of industrial waste can allow production of purified syngas and production of useful by-products, for example by using the thermoselect process (Thermoselect, 2003).

Thermal treatment of WEEE waste plastic includes co-combustion with MSW, pyrolysis, gasification (Kim et al., 2011), cement kilns and metallurgical processes (Al-Salem & Baeyens, 2010). The mixed WEEE waste can be mechanically treated to separate minerals and metals to produce fuel for gasification. In pyrolysis, the metals can be recovered from the char and, with additives, also chlorine, bromine and heavy metal components can be entrapped (Tange & Drohmann, 2004). In the metallurgical processes plastic waste can have two goals: to bring energy to process and work as a reducing agent replacing coke (Al-Salem & Baeyens, 2010). In the cement industry, the WEEE waste can substitute fuel and it has been noted that CaCO3 has a preventative effect on dioxin formation from PVC (Luda et al. 2005).

The incineration of ASR produced from ELV alone is not suitable because of possible carry-over of unburned fines and melting characteristics. Co-incineration with lower heating value wastes enhances the potential and efficiency of incineration in WTE plants. (Vermeulen et al., 2011.) Mancini et al. (2010) investigated full scale gasification of ASR and found that the energy efficiency parameter was 0.61 calculated according to directive 2008/98/EC (EU, 2008). ASR utilization as an alternate fuel to coal in the iron industry results in excellent emission control, because blast furnace process conditions assure the destruction of organic compounds (Galvagno et al., 2001). Microwave and plasma-arc thermal destruction processes can also be used in fluff treatment (Nourreddine, 2007).

#### 3.1.4.2 Applicability of waste to energy technologies

The applicability is divided into three classes: applicable (++), rather unsuitable (+) and unsuitable (-). Applicable means that the technology is commercially available and the waste fraction does not pose major restrictions for operation. Rather unsuitable means that there are some restrictions in technology and/or waste properties are not suitable (for example LHV).

Grate firing is suitable for a many waste fractions. ESR and ASR can have a high LHV and combusting only these waste fractions can harm the grate if it is designed for waste with lower LHV. Fluidized bed combustion, gasification and pyrolysis require pre-treatment of waste and are therefore not suitable for untreated mixed and miscellaneous waste. Cement kiln can accept also wide variety of waste, but it is mostly used for SRF. Biological waste treatment is only suitable for biodegradable waste and thus organic waste, paper and wood are suitable for biological waste treatment. The suitability of WTE technologies for the waste fractions arising from examined waste chains is presented in table 10.

**Table 10.** Suitability of WTE technology for waste fractions from waste chains.

| | Thermal treatment | | | | | Biological treatment | |
|---|---|---|---|---|---|---|---|
| | Grate firing | Fluidized bed | Gasification | Pyrolysis | Cement kiln | Digestion | Fermentation |
| **C&D** | | | | | | | |
| Wood SRF | ++ | ++ | ++ | ++ | ++ | - | + |
| Miscellaneous | ++ | + | + | + | ++ | - | - |
| **C&I** | | | | | | | |
| Paper | ++ | ++ | ++ | ++ | ++ | + | + |
| Mixed | ++ | - | + | + | ++ | - | - |
| Organic | + | + | + | + | + | ++ | ++ |
| **MSW** | | | | | | | |
| Mixed waste | ++ | + | + | + | + | - | - |
| Energy waste | ++ | ++ | ++ | ++ | + | - | - |
| REF / RDF | ++ | ++ | ++ | ++ | ++ | - | - |
| Organic waste | + | + | + | + | + | ++ | ++ |
| Paper | ++ | ++ | ++ | ++ | ++ | + | + |
| **WEEE** | | | | | | | |
| ESR | + | + | ++ | ++ | ++ | - | - |
| Plastics | ++ | ++ | ++ | ++ | ++ | - | - |
| **ELV** | | | | | | | |
| ASR | + | + | ++ | ++ | ++ | - | - |
| Plastic | ++ | ++ | ++ | ++ | ++ | - | - |
| ++ suitable, + poorly suitable, - not suitable | | | | | | | |

### 3.1.5 Problems and challenges arising during the MFA analysis

Knowledge gaps:

- C&D
  - Total waste generation of all C&D fractions
  - Composition changes
  - Information on quantities that are separately collected and/or treated
  - Information on the qualities of produced and residual fractions
  - Shares ending up in unknown treatment.
- MSW
  - Information on the qualities of produced and residual fractions
  - Since paper and cardboard are compiled together in the statistics, it is challenging to estimate how much cardboard and paper are generated and treated
  - Detailed information on how much of each fraction (paper, bio, energy waste etc.) ends up in incineration, energy utilization and REF-production
  - Rather large assumptions as regards process efficiencies for each material group (metal, paper, wood, glass etc.) needing to be made.

- C&I
  - Total waste generation of, glass, metal, plastics and biowaste. Data of glass in this research was the most unreliable. Paper and cardboard are well known.
  - Detailed data for the whole of Finland
  - Proportion ending up in source separation and mixed waste
  - Proportion of generation by different producers
  - Information about end use of different fractions.
- WEEE
  - No or poor data on arising WEEE amounts
  - Collection data available is based on WEEE-categories, not based on actual amounts of products with similar waste qualities.
  - Data on composition of WEEE is lacking.
- ELV
  - Challenge the industry is facing, is that only a part of vehicles which are deregistered receive a certificate of destruction (COD). There is a clear lack of detailed information about the further use of more than 50% of the deregistered cars, and furthermore a clear need for improvements of data quality and the availability of the national vehicle markets.
  - A challenge clearly identified in all value chain analyses is the lack of good quality data. In addition to the need for better data, methodological development is needed.

Development needs:

- C&D
  - A nationwide reporting system for C&D waste management
  - More efficient sorting at source is required in order to increase the yield and improve the quality of products
  - Material recycling of wood waste
  - Material recycling of insulating materials, plasterboard, plastics, packaging and composite materials
  - Recycling of concrete waste to concrete
  - Reduction of treatment residues
  - Utilization rates should be targeted on the whole treatment chain
  - Quality requirements should be taken into account in utilization rates
  - Reporting after processing.
- MSW
  - Separate reporting/statistics system for C&I and MSW
  - Separate reporting for paper and cardboard
  - Reduction of treatment residues
  - Utilization rates should be targeted on the whole treatment chain

    - Quality requirements should be taken into account in utilization rates
    - Improved material recycling of plastics and combined material and energy recycling of biowaste
    - Reporting after processing.
- C&I
    - Nationwide reporting / statistical system of C&I sector's waste generation and separation
        - Consistent (for example HSY's Petra service)
        - Transparent
        - Traceable
    - Nationwide reporting system of C&I waste management
    - Estimating the accuracy of this methodology by comparing results from different years
    - More detailed cost and value analysis.
- WEEE
    - Collection rates need to be enhanced
    - Sorting at source should be enhanced
    - Separation of valuable materials and components.
- ELV
    - Data on imported cars need to be considered in ELV estimation
    - Estimation of new supply and value chains and material flows of electric and hybrid light vehicles
    - Innovations for more efficient material separation, thermo-chemical conversion (gasification and pyrolysis) and recycling/ recovery routes of the residue
    - Utilisation methods of ASR.

## 3.2 Aspects of value formation

Traditionally the value of waste is determined by its treatment requirements and the service provider’s estimation of salvageable materials and their market value. For mixed and hazardous waste streams, the value is usually negative because the cost of collection, transport, and treatment are much higher than the possible benefits from material or energy reclamation. For clean, recyclable materials, the value can be positive because the material value exceeds the overall costs, and the service provider buys the waste from the waste producer if there is true competition on the market. From the recycling systems and processes research and development point of view, the traditional value determination is, however, not sufficient because it does not take into account the whole value potential of the waste.

The value potential of a waste stream can be determined independently of present handling practices and processing technologies. The value potential depends only on the characteristics of the waste stream itself. Each item, part, component, material, and substance in the waste stream has a market value which can be determined using the market price data of second hand products, recycled materials, and raw materials. The value potential of the waste stream is the maximum sum of these market values.

The determination of the value potential gives a whole new set of indicators for the evaluation of the efficiency of recycling systems and processes. For instance, the reclaimed value of materials in the WEEE value chain, which was analysed in this project, was much lower than the value potential. The difference between the potential and the value reclaimed was greatest in precious metals mostly contained in printed circuit boards, plastics, and rare earth metals which were not reclaimed at all. The analysis also showed that meeting the weight-based recycling targets and requirements does not automatically also mean that a high portion of the value potential has been reclaimed. Especially in high value WEEE, most of the value potential is in a very small part of the total mass.

In addition, analysis of the value potential gives ideas for new types of business development. A typical example of the effect of value potential on the business model comes from the ELV recycling industry. If the average scrapping age is low, which means that the scrapped cars are quite new, the primary business interest is in reclaiming usable spare parts and high value components, because their value potential is much higher than the value of materials and substances in these parts and components. On the other hand, if the average scrapping age is high, as in Finland at the moment, the value potential of old parts is low and the primary business interest is in material reclamation. This in turn creates new challenges for the industry, because it will be very difficult to achieve the new ELV recycling targets with the present technologies, especially as the material contents of ELVs is continually changing towards a lower material reclamation potential.

The value potential approach used in the project to describe and analyse the waste streams has proved to be useful, especially in the cases when the waste stream consists of complicated products with common features such as cars or electronic equipment of a certain type. It is also suitable in cases when the above-mentioned discarded products form a more general grouping, like high- or low-value WEEE, or in cases when the waste stream can also have other than material and substance values, such as demolition waste. For mixed waste streams with relatively low material values, like mixed MSW and C&I waste, the value potential approach does not provide very much new information.

## 3.3 Life cycle and BAT aspects of waste chains

### 3.3.1 Life cycle climate change impacts of the selected waste chains

The environmental impacts considered the most relevant and important to be included in the LCA for the NeReMa waste chains were climate change (CC) impacts, natural resources use and toxic impacts caused by hazardous substances. The CC impacts were assessed for all waste chains excluding the ELV waste chain and natural resources use for the C&D waste chain. Hazardous substances were assessed qualitatively for the C&D and WEEE waste chains (presented in the waste chains in Chapter 3.1.2). The aim of the LCA was to provide an estimate of the potential impacts of the waste chains and to highlight the life cycle phases (processes or activities) or waste flows causing the highest contributions to the impacts. The waste chains were divided into five life cycle phases:

- waste generation
- pre-treatment (crushing/shredding and separation)
- recovery (both material and energy recovery) of the separated materials
- treatment of waste (landfilling)
- avoiding virgin production or energy generation.

Transportation was not included in the assessments. The role of transportation has in many waste management LCAs been shown to be of minor importance compared to the overall impacts (e.g. Myllymaa et al. 2008). The role may, however, increase with recycling demands for more waste fractions requiring separate collection.

Due to the data gaps and uncertainties involved in the assessment, the results can only be considered as directional. Uncertainty is introduced by a lack of data on the composition and amounts of waste fractions included in the waste chains and also on the purity of the materials produced by the waste chains intended for recovery. The latter affects the usability of the waste chain "products" in e.g. metals manufacturing or earth construction, and the emissions avoided by compensating virgin production with them may be overestimated. The estimations of potential for avoiding emissions by energy recovery of waste are based on the assumption that waste replaces fossil fuels. When moving towards an increasing use of bio-based energy, this assumption does not hold any more.

#### 3.3.1.1 Results

The CC impact assessment performed for the C&D, MSW, C&I and WEEE waste chains with the assumptions made (described in the analysis report Dahlbo et al. 2012) showed that the life cycle phase pre-treatment produces 2–8% of the overall CC impacts produced by waste chains. The contribution of the treatment phase (i.e. landfilling) varies from < 1% to 53% and of the recovery phase 39–92% of the overall CC impacts produced by the waste chains.

The majority of the impacts from the treatment phase originate from landfilling mixed waste, but also from landfilling residues and rejects produced in various processes along the waste chains. The majority of the impacts produced by the value chains originate from the metals, REF and mixed waste fractions for the C&D chain (Table 11), from the paper, mixed waste (energy recovery), glass and REF fractions for the MSW chain, from the cardboard, plastics and mixed waste fractions for the C&I chain and from the metals and plastics and rubber fractions for the WEEE chain. Most of the potential for avoiding impacts through materials recovery are connected to metals, paper-and cardboard fractions whereas potential for avoiding impacts through energy recovery are connected to the wood, REF, mixed waste and plastics fractions (Table 11). When combining the produced and the potentially avoided CC impacts, it may be considered that C&D, C&I and WEEE chains all have the potential for decreasing impacts more than they produce. For the MSW chain the produced impacts are almost equal to the potentially avoided impacts.

**Table 11.** Contributions of different waste fractions to the CC impacts produced or potentially avoided by the value chains C&D, MSW, C&I and WEEE.

| | Contribution of waste fractions to the overall impacts produced or potentially avoided by the value chain | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Metals | Glass | Paper | Cardboard | Organic/ biowaste | Wood | REF | Mixed waste | Concrete, mineral | Plastics | Sum |
| Produced; C&D | 26 % | | | | | 5 % | 34 % | 34 % | 2 % | | 100 % |
| Produced; MSW | 2 % | 4 % | 20 % | 1 % | 1 % | 0,2 % | 9 % | 63 % | | | 100 % |
| Produced; C&I | 4 % | 1 % | | 28 % | 4 % | 1 % | | 49 % | | 14 % | 100 % |
| Produced; WEEE | 54 % | | | | | 0,2 % | | | | 46 % | 100 % |
| Potential for avoiding; C&D | 22 % | | | | | 46 % | 28 % | 3 % | 1 % | | 100 % |
| Potential for avoiding; MSW | 7 % | 5 % | 25 % | 10 % | 6 % | 8 % | 13 % | 24 % | | | 100 % |
| Potential for avoiding; C&I | 9 % | 1 % | | 49 % | 13 % | 12 % | | 14 % | | 4 % | 100 % |
| Potential for avoiding; WEEE | 86 % | | | | | 1 % | | | | 12 % | 100 % |

The performances of the waste chains can be enhanced by decreasing the landfilling of biodegradable fractions, rejects and residues and increasing the recycling of especially metals, paper and cardboard fractions. Plastics are at present mainly recovered as energy, but due to high emissions from plastics incineration, the benefits of energy recovery remain small. Recycling of plastics would decrease the impacts produced from recovery and increase the impacts potentially avoided. Due to the heterogeneity of plastics, more processing would be needed in the pre-treatment phase, but observing the minor share of pre-treatment of the overall impacts of waste chains, from an environmental point of view this would still be beneficial.

### 3.3.2 The use of life cycle costing in evaluating waste chains

During the NeReMa life cycle costing (LCC) was demonstrated alongside environmental LCA. LCC complements the LCA in sustainability assessment by evaluating also the economic sustainability. However LCC could not be fully implemented, due to the limited access to company accounting data. Therefore, only the LCC approach was demonstrated by using the data available from the LCA.

The product flows collected for the LCA of construction and demolition (C&D) waste were converted into costs by multiplying them with average cost data for those flows. The average cost data was obtained from scrap metal purchasers' web pages, from machinery costing tools, transport statistics and from infrastructure suppliers. The costs must, therefore, be considered to be approximate only.

The overall costs are presented in Figure 31. Based on the results, the overall recycling of C&D waste is profitable, especially because of the revenues from scrap metal and energy produced from wood and miscellaneous waste. The recycling of mineral and mixed wastes was found to be non-profitable without fees. However, it should be noted that the costs included in the analysis might represent only 70% of the overall costs (based on limited information from one company).

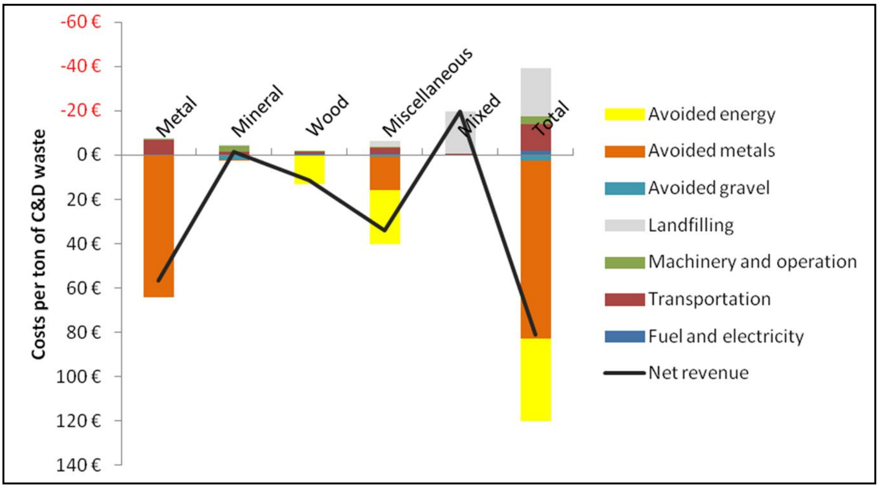



**Figure 31.** Costs estimated from the material and energy flows documented in the LCA.

Using macroeconomic modelling (ENVIMAT), it was shown that the revenues are formed from the avoided production of natural gas and forest biomass fuel, imported ores and metal scrap as well as the domestic metal industry. The economic viability of recycling of C&D waste is, therefore, highly dependent on the price formation of global metal ores. With increasing resource scarcity, the recycling process is likely to become more profitable.

The LCC exercise demonstrated that it is not possible to perform a proper LCC without full collaboration from the companies involved. The cost data is often regarded as confidential, and therefore is not available for public research. However, the tool could be an appropriate management tool for company internal decision-making. By employing environmental LCC the managers can map the "economic landscape" of their supply chain and prepare for possible macroeconomic changes.

### 3.3.3 BAT aspects in evaluating waste chains

The waste chains originate either from different activities, such as C&D, MSW and C&I or on the bases of the type of waste (WEEE and ELV). Widening the perspective of assessments to include waste chains and parallel processes for different waste fractions provides the possibility of rethinking the outcome of the waste chains in a new way and recognizing the hot spots in the wider context. An environmentally efficient waste management chain has a twofold target: treatment of the waste (= raw material) and the end product to be used elsewhere. Therefore, the BAT criteria include also material recovery rate and quality requirements for the recovered material in addition to selected environmental emissions. In the waste management business also the market dynamics unavoidably affects the criteria and the outcome of the assessment. The LCA tool can be applied for identifying the hot spots, i.e., activities or processes contributing most to the environmental performance of the whole chain.

Screening of waste-chains from a BAT viewpoint was performed over C&D and WEEE chains but the definition of BAT criteria was discussed only at a theoretical level due to the lack of reliable environmental performance data. Collected waste-chain information is presented in the analysis report of this study.

Considering the specific features of material recovery activities, the BAT assessment procedure for waste management chains can be derived from the five step general installation level BAT assessment process (EC, 2010). This iterative process consists of identification of the waste-chain type (origin of the waste, waste type) and the overall target for the recovery process (waste treatment, material recovery), identification of the requirements set by the end use of the product(s) taking into account technical, environmental, quality and market based issues, identification of the activities of processes most contributing the environmental performance of the chain and selection of the criteria to describe BAT for the waste-chain at general level.

## 3.4 Monitoring

### 3.4.1 The current situation in Finland

Currently, the separation of waste materials is based on source separation carried out manually on-site and mainly mechanical separation methods based on different physical properties of the waste, such as magnetic properties, density, size, and optical properties. In many cases, manual steps are still needed either for coarse pre-separation or for removal of impurities that are difficult to separate with current automatic methods.

The main challenges are:

- the materials produced by source separation practically always contain impurities and further purification steps are needed

- poor quality of the produced materials due to the insufficient separation of impurities in the current treatment chains
- large amounts of mixed residues produced in recycling processes
- material losses due to the insufficient separation.

Development and/or introduction of new detection methods suitable for solid materials could be an essential part of the solution, but not the whole solution. Efficient integration of automatic detection also calls for a redesign of the process chains.

At present, only a few monitoring and detection techniques are in use in the Finnish waste management and recycling sector. Typically, the monitoring is based on visual observations of arriving waste loads and in some cases on handheld metal detection devices. The quality control of the recovered product (sorted waste fraction) is commonly implemented by sampling and laboratory tests. There are some exceptions where the integration of automatic detection methods to the process has been started. Although there are various commercial solutions on the market, in many cases it is still difficult to find an efficient or even a working solution to specific needs. One of the challenges is that most of the current optical detection methods are hampered by contaminations or visual obstructions.

### 3.4.2 Summary of the identification methods

Many of the identification methods are used in combination with another method to improve the quality of the end product, or sequentially in order to remove several different materials from the waste stream.

- Colour cameras are typically combined with some other identification method, such as EMS. It identifies e.g. different types of metals, plastics, wood, and glass utilizing the different colours of the different types. (The high spatial resolution in conjunction with precise colour measurement enables sorting complex material streams of used electrical devices and the recovery of nonferrous metals with a high purity.)

- DE-XRT (Dual energy X-ray transmission) measures the average atomic number of the fraction. The DE-XRT identifies organic and inorganic fractions, metals, chlorine, and bromine.

- EMS (Electromagnetic sensor) measures the electrical properties of metals with an alternating magnetic field. The EMS identifies different non-ferrous metals and sorts them based on electrical conductivity: high, medium and low conductivity. The benefit of the EMS is that coatings or other impurities on metal, as well as contamination such as dust or dirt, does not impede identification.

- Hyperspectral cameras collect and process information from across the electromagnetic spectrum, measuring several wavebands simultaneously and recording a full spectrum for each pixel of the image. The composition and properties of the waste stream is rapidly mapped, and the system is able to identify e.g. black objects (plastic types, rubber).

- IR (Infrared spectroscopy) is based on the ability of the molecules to absorb infrared radiation, which varies depending on the material. The method is suitable for e.g. separate different plastic types from each other; it is sensitive for moisture. NIR (Near infrared spectroscopy) has many online applications but is not suitable for dark coloured objects (no identification). MIR (Mid infrared spectroscopy), again, identifies dark coloured fractions but has no good online applications.
- LIBS (Laser-induced breakdown spectroscopy) is based on a high-power laser producing a plasma flash which vaporizes the surface of the sample. Different materials emit different wavelengths of energy enabling identification of e.g. heavy metals, halogens (bromine and chlorine), and different plastic types.
- XRF (X-ray fluorescence) is based on X-rays that are absorbed by the sample, which generate fluorescence which varies depending on the material and the additives. XRF can be used to detect flame retardants, heavy metals and PVC (chlorine) for the identification of treated wood, plastic, and additives.
- XRT (X-ray transmission) identifies heavy and light atoms. The XRT can be used for e.g. sorting out PVC, materials with flame retardants, glass and metals from energy waste.

### 3.4.3 Development needs

The separation of valuable materials is becoming more important both due to increasing recovery targets and to the growing recycling business and the increased value of recovered materials. Increased recovery is enabled through improved identification and separation technologies which are needed in order to reduce the contamination of the sorted waste while also reducing the losses.

- The mechanical separation of household waste is becoming more important especially due to the ban on landfilling organic waste which is to come into force in Finland. The majority of the mixed waste will be incinerated, and valuable materials, incombustible waste and contaminants will have to be removed in advance.
- The identification of harmful fractions from the energy waste, e.g. treated wood, metals and PVC, as these fractions cause problems in the incineration process and reduce the utilization possibilities for the ash.
- Separation of the metals from REF and mixed waste.

- Real-time quality monitoring systems (with online communication systems) for different waste streams.
- Identification of different plastic types including black and dark plastics, as well as contaminants, such as chlorine, flame retardants and heavy metals.
- Improved identification to ease the separation of materials in the recycling of WEEE and ELV.

***REF production – quality control***

*The quality of the energy waste and mixed waste is monitored by visual estimation when the waste is delivered to the treatment plant. After treatment, the properties of the final REF product are determined in a laboratory by sampling and analysing. REF has its own standard for quality determination (SFS 5875) with three different quality classes: REF I, REF II, and REF III, of which REF I is of the best quality. The classification is based on seven different impurities. The sampling and analysis methods and limit values are presented in the standard. (SFS 5875:2000)*

*The fuel properties are dependent on combustion properties such as moisture and calorific value, as well as harmful contaminations. The problematic fractions are e.g. treated wood, packages containing aluminium, PVC plastic and fractions containing flame retardants. (Laine-Ylijoki et al., 2003; Ajanko et al., 2005) The moisture content of the REF is measured and communicated in real time online; the measurement can be done e.g. with near infrared spectroscopy (NIR) or microwave permittivity measurement (Järvinen et al. 2007). The concentrations of the harmful fractions (chlorine, aluminium and heavy metals) are measurable with the XRF. The calorific value measurement is commonly based on sampling and laboratory analyses, which cannot be carried out in realtime.*

# 4. Towards resource-efficient recycling

## 4.1 Targets

The EU waste directives set quantified recycling targets for approximately 47% of the around 3 billion tonnes of waste generated annually in the EU Member States plus Norway, and at the moment about 50% of the targeted wastes are recycled. (EEA SOER, 2010) The EU Commission will review all recycling and recovery targets during 2012. Waste chain-specific recycling targets are highlighted below. Recycling targets are expected to affect product design and innovations in the field. In practice, the influence of recycling targets has been indirect and not as significant as was expected. It is possible that in future there will be even more specific targets, for example for different product groups.

- **C&D:** The EU waste directive (EU, 2008) sets a target for recycling of non-hazardous construction and demolition waste to a minimum of 70% by weight by 2020. This will be adapted to the Finnish waste decree. The target will be an inconclusive target concerning all parties operating with house building waste management. The large proportion of wood in the Finnish C&D waste makes the 70% recycling target difficult to achieve.
- **MSW:** The EU waste directive (EU, 2008) sets a target for waste materials such as at least paper, metal, plastic and glass from households and from other origins. By 2020 a minimum of overall 50% by weight should be recycled. This target will be adapted to the Finnish waste decree as an inconclusive target concerning all parties operating with municipal waste management. In practice, municipalities, producers under producer responsibility and other entrepreneurs together are in charge of meeting the target.
- **WEEE:** The so-called WEEE directive (EU, 2003) requires member states to collect waste electronic devices separately. The European Commission has proposed a recast (17367/08) (EU 2008c.), which would adapt the current collection target (4 kg WEEE per inhabitant) to the size and economic situation of individual EU countries. According to the agreement reached with the Environmental Council on 14.3.2011, mem-

ber states should annually collect 45% of the average weight of EEE placed on their national markets. This would take effect four years after the entry into force of the revised law. Four years later (2016), member states are to achieve a 65% collection rate. Some EU states in which consumers use fewer electronic devices may achieve the targets with some flexibility. A final decision is expected to be taken at the beginning of 2012. One of the main elements of the deal is a change in the way the collection target is calculated.

- **ELV:** A Government Decree on ELVs (581/2004) sets a target by 2015, for all ELVs oaf minimum of 95% reuse and recovery per year, and a minimum of 85% reuse and recycling per year. In 2009, the reuse and recycling rate was 81% in Finland and the reuse and recovery rate 82% of the number of ELVs collected. It is estimated that more than half of the ELVs do not end up in producers´ collection statistics.

## 4.2 Drivers for change

### 4.2.1 Megatrends

The Finnish Ministry of Environment (2010) has analysed the current and established trends concerning material flows . Material flows in developing countries such as China, India and Brazil are expected to grow and industrialized countries are asked to decrease their material flows. According to the ministry, negative effects of growing material flows are increasing and the need for a global policy is recognized. The use of natural resources and resource efficiency are both global and European drivers for a more material-efficient waste sector. Waste is seen as a resource, and there is a growing global demand for both primary and waste-derived materials.

#### 4.2.1.1 National strategies

National strategies affecting recycling and waste management in the future include the National Waste Plan until 2016, the Natural Resource Strategy for Finland, the Government Report to Parliament on Natural Resources, the working group on bio-economy supporting the national resource strategy set by the Ministry of Employment and the Economy, Minerals strategy and Climate Strategies.

As a conclusion to the strategies mentioned above, it can be stated that there is great concern regarding our extensive use of natural resources in Finland. As a response to that concern, there are several initiatives on material efficiency, developing more closed material cycles and using waste as a source of material. The strategies are more of a voluntary nature than strictly binding. However, they enlighten the future prospects of the use of natural resources and materials.

#### 4.2.1.2 EU trends and strategies

European environmental and waste legislation has become stricter over the past decade, demanding more efficient waste treatment and increased recovery rates. This facilitates the market for waste management and recycling. As a part of the Europe 2020 strategy, the EU launched a flagship initiative for sustainable growth and a roadmap to a resource-efficient Europe in 2011. The flagship initiative underlines the fundamental meaning of natural resources to the functioning of the economy and quality of life. One of the roadmap measures is turning waste into a resource. Waste management should be improved to make better use of resources, and higher priority needs to be given to reuse and recycling. This opens up new markets and jobs, as well as encouraging less dependence on imports of raw materials and lower impacts on the environment.

Apart from the environmental aspects, the access to natural resources is also a major issue internationally. Besides metals, also phosphorus depletion is a growing concern. Recently, leakage of valuable resources through exports of end-of life or second-hand products has been noted as an important enviro-economic problem, especially for cars and electrical and electronic appliances, and this problem is now also increasingly recognized as a threat to the supply of Europe with critical metals. The question of waste exports goes hand in hand with the question of recycling markets. One reason for growing exports is the existence of major markets for recyclables overseas. For Europe, this means missed opportunities and possible risks in terms of raw material supply. There is a need to promote recycling markets and address the problems related to waste exports. Future policies need to improve not only the quantity of recycled waste but also its quality in order to further reduce the environmental impacts of waste. Development of quality standards for recycled materials where these are not yet available, eco-design of products that improves recyclability, and detoxification of products can all play roles in moving closer to this aim. (EEA SOER, 2010; EEA, 2010)

#### 4.2.1.3 Global trends

Global trends of increased wealth, industrialization, urbanization and population growth result in increasing consumption, with consequences such as increased waste generation and an increased demand for raw materials. These trends as well as differences in the waste generation between urban and rural people are stronger in developing countries than in developed countries. In densely inhabited areas. poorly managed waste can create serious environmental and health problems. (Hietanen et al., 2006)

The increased utilization of natural resources together with the uneven distribution of resources, political instability in some major producer countries, and other political factors will reduce the availability of virgin raw materials; the availability of high-tech materials, bio based materials and phosphorous are at risk. The collective ecological footprint of the global population already exceeds the Earth’s capacity and is rising. The risks related to reduced material availability and growing prices have led to growing political and private speculation in raw materials, resulting in high price volatility, which in turn complicates the recycling business. Since 2005, raw material prices have been quite volatile, as illustrated in Figure 32.

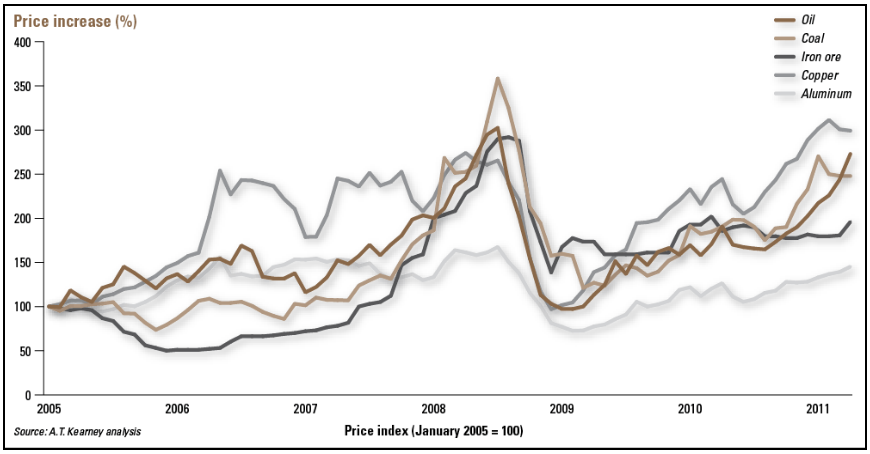



**Figure 32.** The volatility of raw material prices (Shuh et al., 2011)

The increasing price of natural resources has led to improved energy and material efficiency in, for example, production processes. On the other hand, the growing complexity and miniaturisation of products as well as the more efficient processing of raw materials has led to decreasing recyclability of the generated waste.

Moliis et al. (2009) estimates the global annual market growth of the waste management sector to be approximately 6%. In developing countries the market growth is mainly in arranging basic waste management, while developed countries are increasing their recycling rates and developing new and improved technologies for waste management (Moliis et al., 2009).

The recycling business (as other business activities) needs flexibility in order to adapt to the rapid changes of the operational environment and to find proper ways to manage these. One of the major trends in the waste sector in developed countries is the integration of waste services into environmental service concepts, as well as integration with the energy and material sectors. In the future, various integrated treatment concepts will increasingly gain ground, including, for example, combined treatment of various biogenic wastes. The borders of sectors will fade away, giving space for new industrial symbiosis type networks. The waste sector is also developing towards greater technology intensity, increasing the demand for ICT technologies supporting the services and processes. (Hietanen et al., 2006; Frost & Sullivan, 2006)

Especially in developed countries, people's attitudes, awareness and environmental concern is increasing. The power of public opinion can be seen in stricter legislation and improved waste management services. Although people still prefer not to change their consumption patterns, but to rather increase on-site sorting and recycling, Hietanen et al. (2006) foresee, a change in people's attitudes, resulting in increasing consumption of services and tailored products. The main problem for the waste management sector will be to find economical business solutions for the decreasing waste volumes.

#### 4.2.1.4 New technologies

Technological developments, such as nanotechnology, biotechnology or information technology, may have a notable significance for the waste sector. Nanotechnology is an interesting factor affecting the waste management sector. On the one hand, nanotechnology offers the possibility of enhancing material efficiency by reducing the use of raw materials, and it may also offer new possibilities for waste treatment technology. On the other hand, it is uncertain how nanoparticles affect the recycling or energy recovery of products containing nanomaterials. As all the other products eventually come to the end of their useful life, so also do products containing nanomaterials. It is important to consider how various nanomaterials will be disposed of and treated at the end of their use. What is more, other technological developments, such as biotechnology or information technology, may have notable significance for the waste sector. One of the challenges of an increased use of bio-based products is the increased consumption of nutrients and potential for soil degradation, leading to the need for better management of nutrient cycles and organic matter.

### 4.2.2 Specific drivers and trends for C&D and WEEE waste chains

In an EEA study of classification of recycling policy measures in relation to the actual recycling achieved, Finland is ranked as level 2. Ahead of Finland are high performers such as Germany, Belgium and Denmark. Finland is ranked as level 3 for packaging waste and WEEE and level 2 for municipal solid waste and biodegradable municipal waste. For construction and demolition waste Finland is ranked as level 4. The future trend concerning these specific waste streams in Finland is expected to be a stricter waste policy. (Tojo & Fischer, 2011.)

### 4.2.3 WEEE

Electrical and electronic equipment waste is one of the fastest growing waste streams in the EU. The revision of the WEEE directive (EU, 2003) is only just being carried out. The WEEE directive currently only applies to a specific list of products. There is an agreement to broaden the scope of the law after six years. The new WEEE directive also requires large electronic and electrical goods shops to set up collection points for used small equipment. This is expected to make recycling easier for citizens.

Eco-design of products, end of waste criteria, resource efficiency and the leakage of critical metals outside Europe are important factors that will affect WEEE regulation in the near future. Also, harmful substances in products and associated regulations must be affected. They may be an obstacle that hampers recycling of WEEE. The short life cycle of products is a problem and it affects the growth of WEEE amounts. It is difficult to enhance repair activities due to a lack of spare parts for old products. The legislation on international shipments of wastes is likely to become stricter concerning WEEE shipments to avoid environmental risks and harmful waste management activities, especially in developing countries. When the holder of the material claims that he intends to ship used EEE and not WEEE, he should prove his claim that the equipment is not waste. (Interview data.)

#### 4.2.3.1 C&D

There is a specific interest on developing the regulation on C&D waste in Finland. The ministry of environment has published a report on material efficiency in construction and demolition sector (Kojo & Lilja, 2011) and is about to establish a working group to take the proposed actions further. The main policy driver, the 70% recycling target for construction and demolition waste is challenging to achieve in Finland due to the proportion of wood waste. The ban on organic waste going to landfills is especially expected to affect the management of waste wood. The Land Use and Building Act and the Building Code are essential drivers in the construction and demolition sector. Also, product design is an important factor. Finland is considered to be a small market area, and there are problems with the availability of recycled products.

The Ministry of Environment is starting a project to improve the database and statistics for C&D waste generation in order to reduce the uncertainties in the information concerning C&D waste generation in Finland.

The large variation in the proficiency of the developers is challenging for the improvement of material efficiency and recycling in the construction sector. Improvement of professional capabilities is one of the questions for a working group to enhance material efficiency of C&D waste to be appointed by the Ministry of Environment. (Interview data)

According to a report published by European Commission (European Commission, 2011), the main economic barrier to recycling C&D waste is the high availability and low cost of virgin raw materials. To overcome this, landfilling of C&D waste is likely to be made unattractive. An alternative is to increase the price of primary raw materials with taxes to make recycling more competitive. The report also suggests that setting End-of-Waste criteria for certain types of C&D waste could contribute to increasing the market for secondary raw materials obtained from C&D waste.

## 4.3 Challenges and development opportunities

### 4.3.1 Waste composition and data quality

Waste quality is affected by several factors such as product composition and contaminations, consumption patterns, etc. These factors and their trends need to be identified and impacts on the waste flows in the long run assessed in order to be able to bring up the development needs for the waste management and recovery process technologies.

A challenge clearly identified in all waste chain analyses is the lack of good quality data. In worst cases applicable data does not exist at all. Most of the available data is very general and imprecise in nature, and when detailed data is available its representativeness is usually poor. The main reasons for poor data quality are, for instance, the heterogeneity of waste streams, which makes sampling very challenging, and the low value of many streams makes monitoring quite unattractive. As materials from several waste streams are jointly processed, it is impossible to keep track of the different streams through the treatment processes.

There is a need for better data quantity and quality analyses of the waste streams, as well as for tools to keep track of the different waste streams during processing. This would enable better efficiency analyses of the different streams, which would enable identification of the most important raw material sources. Research is needed to produce reliable data on the quantity, composition and quality of waste material flows both prior to and after sorting and treatment processes.

Improved quantity and quality of the waste streams would facilitate the planning and implementation of research and development projects, as well as corporate and public decision-making. Although there are methods for waste stream monitoring, the costs are too high in comparison to the benefits. Low-cost real-time monitoring technologies could provide good quality data, but improved monitoring is not compulsory, and this development is mainly in the interest of researchers and decision-makers.

### 4.3.2 Waste management processes

A key challenge for the waste management sector is to increase recycling as a way to reduce the overall use of natural resources. This calls for intensified sorting both with more efficient technologies and with guidance on the behaviour of waste producers (people), but also consideration of the recyclability of products already in the design phase. Sustainable product design is the first step towards increased recycling. Sustainable design aims at mapping the whole material chain as a closed-loop cycle already at design stage, enabling easy recovery of the materials at the end of the life-span.

Reuse would in many cases be more energy and material efficient solution than recycling. The potential for reuse of construction elements in particular should be better exploited.

With increased recovery the benefits from recycling would increase and probably several times over compensate for the increased emissions from pre-treatment. The behaviour of waste producers can best be assessed by methods used in the human sciences, which in the future should more intensively be connected to research focusing on waste management.

Typical for waste and recycling chains is the large number of stakeholders and decision makers involved, and the many different types of criteria used in decision making. In addition to economic criteria, environmental, social, and policy criteria also play an important role in decisions which guide the material flows through the recycling and waste management systems.

#### 4.3.2.1 Emerging technologies

Mechanical processes operate on the basis of physical properties, which is why physics also creates boundaries to the operation. Therefore, new equipment and methods are challenging to create, and the focus of new technologies is shifted towards monitoring/identification, improved processes, combining and controlling flows and rethinking treatment chains. Improved chain management, including real-time monitoring of the different flows as well as sophisticated treatment processes and process chains focused on certain products, enables gaining increased value from the recovered materials. Contaminations should be removed and if possible different fractions pre-separated at an early stage of the sorting and processing in order to improve the quality of the end product and to enable efficient recovery of materials which concentrations are low in the feed e.g. critical metals.

In order to enable the development of economically viable and sustainable recycling processes, modelling tools and methodologies are needed which integrate a systematic analysis of the value of waste streams and an analysis of the economic and environmental sustainability of recycling processes and concepts. Analysis of different business scenarios and use of system dynamic modelling concepts enables an understanding of the viability of the concepts in changing the business environment.

The availability of data produced can be improved by the creation of multipurpose databases that can be used by different parties and by different assessment programs on the same platform. The potential applications may include identification and assessment of the suitability of waste streams for the raw materials of other industries, sustainability assessments, modelling of recycling and reuse processes, waste foresight modelling, scenario analyses, etc.

Improved separation technologies enable increased recovery of valuable materials. For example, the separation of valuable materials, incombustible waste and contaminants from REF and mixed waste facilitates incineration and recovery.

Contaminants, such as treated wood, metals and PVC cause problems in the incineration process and lessen the utilization possibilities of the ash, which is why they should be separated more efficiently.

Improved identification methods enable more efficient separation results and higher quality and value recovered materials. Especially important is, for example, the identification of different plastic types, including black and dark plastics, as well as contaminations such as chlorine, flame retardants and heavy metals. There is also a need for improved identification to ease the separation of valuable materials in the recycling of WEEE and ELV.

### 4.3.3 Key materials for increasing resource efficiency

When it comes to resource efficiency and the efficient use of natural resources, those critical resources and waste streams with the potential to substitute virgin natural resources should be studied. Waste wood and plastic are regarded as important resources, which currently have quite low recovery rates, but with high potentials for the future. Also, the WEEE stream, including metals and critical materials, should be better utilised. Besides large quantities of copper, strategic materials, including critical metals can be recovered from this waste stream, helping to cover future demand.

Legislation related to the organic landfill ban, material recycling targets and reductions of greenhouse gas emissions require improved separation and increased recycling of organic materials. As organic materials cannot be landfilled any longer, they need to be identified and separated for treatment. This will require material and/or energy recovery solutions for biowaste. Also, the EU waste directive's target for recycling of 70% of C&D waste requires recycling of the waste wood and finding a new utilisation for the recovered wood material. Furthermore, as plastic materials cannot be landfilled any longer, the separation and recovery of plastics in MSW, C&D, and WEEE will become necessary.

The depletion of natural resources has generated interest in reutilising materials, which have been discarded at landfills. Waste in landfill deposits can be seen as a resource, which could compensate for virgin resource use. In order to evaluate the utilisation potential of this waste, more information is needed regarding the properties and material capacity of this landfilled waste. Methodologies need to be developed for identifying recyclable materials in landfill deposits.

### 4.3.4 Markets for recovered materials and products

How different policy tools affect people's willingness to recycle and buy recycled products is an interesting question. Recycling decreases the use of natural resources only if products made from recycled materials compensate for products made from virgin materials. Recycled materials are not always compatible with virgin materials, and consumers do not always acknowledge recycled products as being of as good a quality as virgin products. Quality control systems should be developed to verify the quality of recycled products. This is also a business opportunity, since the need for auditing experts is clear.

The obstacles and drivers for recycling need to be analysed at a national level. One recognized obstacle is the lack of a market for recovered materials; currently the supply and demand of waste materials do not meet; the producer and potential user do not know each other.

In current Finnish conditions, only a few materials, such as metals, paper, and cardboard, are truly economically feasible to recycle without any government incentives. Increasing the recovery rate of these materials, which have an existing market demand, should be emphasised. The market demand for other materials may, however, increase because of the changes in business environment. Attitudes towards on-site sorting and recycling are also important for the development of the recycling market.

Metals are a commercially important waste stream, mainly due to the diminishing global metal resources, but also due to the energy-intensive process of mining and processing metals and the significantly lower energy demand of the recycling process. The additional benefit is that metals will not degrade during the recycling process. WEEE is important due to the content of precious metals; but the separation process is mechanical and quite labour-intensive and therefore expensive in developed countries.

Strategic materials, including critical metals, which have a limited global availability, should be recovered from the waste stream in order to cover future demand E.g. in renewable energy technologies, such as wind energy generators and PV cells, the global resources of some critical materials are not sufficient to cover future demand. To understand the future business potential of recycling of critical materials, the market in virgin materials should also be analysed and substitution opportunities of the critical materials identified and analysed as far as possible.

### 4.3.5 Markets for technologies and services

The strict European waste legislation demands major improvements in the waste treatment methods, thus, creating markets for technology providers. Restrictions and increased landfilling fees resulting in reduced landfilling rates create a demand for alternative waste treatment methods. The recycling and waste management market in emerging countries is rapidly growing. Therefore the development of advanced recycling technologies and concepts would be a competitive advantage for Finnish industry on the international market. The value of exported technologies and services could be considerably higher than the value of materials recycled in Finland.

Treatment capacity is dependent on material demand; the demand needs to increase steadily before investments in new facilities become profitable. To meet these kinds of challenges various opportunities for increasing and concentrating material input should be studied. These include e.g. concepts combining small-scale pre-treatment and large-scale processing of waste materials, integration of waste streams from various sources and import of waste.

Many municipal and industrial customers have started to increase their demands on services, requiring holistic solutions for all their waste management needs. Currently, the most successful companies on the European waste markets are focusing on an improved service level with holistic solutions. Higher value services make possible increased business opportunities without increasing waste generation levels.

As the Kyoto protocol has come into force, the steering mechanisms, such as the Clean Development Mechanism (CDM) can be utilised in the waste management sector, e.g. for the construction of recycling plants and landfill gas utilisation projects abroad.

***Opportunities in foreign markets***

***China***

*The combination of population growth, urbanisation and economic growth is creating tremendous growth in Chinese waste generation. The growing waste volumes in China are creating increasing pressure on waste management systems, which are not keeping up with the development. This has led to an increasingly inadequate capacity of waste collection and transport vehicles, which is restricting the development and utilisation of the waste treatment facilities. China also has a significant informal sector, removing the recyclables and affecting the composition of the waste stream. However, the scavenging might decline in the future, but then waste sorting will become a challenge, as no systematic waste separation has been introduced.*

*In order to achieve success on the Chinese markets it is important to have a good understanding of the markets, to have good local partners and to have a good contact network. The Chinese are looking for holistic problem-solving solutions. Since many developed countries have superior environmental protection, China is taking advantage of the know-how of foreign players, creating a market for international consulting and technology companies on the waste management sector.*

***Russia***

*Russian waste volumes are continuously increasing, creating a demand for increased waste management capacity. Russian waste management has a lower capacity than its waste generation, and needs to be increased. The majority of the current players in the market offer only collection and transport services, leaving the whole separation, recycling and recovery sector wide open for new players. There is a demand for safe landfills without leakage to the environment, and also for waste recovery and recycling plants. As the majority of the waste is collected as mixed, there is also a great demand for waste sorting plants, as well as on-site sorting and separate collection systems.*

*Municipal councils in large cities are increasingly open to development of the waste management system by the introduction of new and more efficient technologies. In order to finance these projects, the authorities are increasingly interested in PPP schemes. The interest of international investors is also growing, and this could enable large-scale investments, as the government seems reluctant to increase the waste management budget.*

# 5. Summary and conclusions

## 5.1 Background and approach of the study

Global trends result in increasing consumption with consequences such as increased waste generation and increased demand for raw materials. The centre of gravity of the world economy has moved towards the market in emerging countries. The waste management market is growing especially in Asia and South America, and the focus is also shifting to African countries. Waste is increasingly becoming a good which is traded around the world. The market drivers for the demand and prices of recyclables vary substantially between different materials, following the world market prices of corresponding virgin raw materials. The availability risks of materials have led to growing political and private speculation in raw materials, resulting in high price volatility.

These megatrends reflect the environmental policies and regulations which strongly affect the operational environment in the waste management chains. Finnish waste legislation is largely based on EU legislation; both are largely based on the waste hierarchy, which is a theory of the desirability of different waste management and treatment strategies. The main objective is to avoid waste generation. Material recycling is seen as the best solution for waste treatment, followed by energy recovery and disposal as the least favourable option. Both Finnish and EU waste legislation have specific targets for the treatment of different waste streams. Waste chain-specific recycling targets are expected to affect product design and innovations in the field. It is possible that in future there will be even more specific targets, for example for different product groups. In several other business sectors, the influence of financiers and stakeholders has grown notably compared with legislation. This trend may be probable also in the currently strongly legislation-driven waste sector.

In this project, five waste operational chains have been analysed. The analysis methods used were Material Flow Analysis (MFA), Life Cycle Analysis (LCA) and Life Cycle Cost analysis (LCC). In addition, a more detailed value formation analysis was carried out for selected chains. In order to create the analyses, the operational features of each chain as well as current and future requirements of the operational environment have been examined. For all waste streams, the main characteristics, material content, treatment technologies and future estimations have been identified. The utilisation and losses of the material potential have been analysed, as also the energy recovery potential for each waste chain.

The LCA analysis focused on the life cycle environmental impacts identified as the most relevant in waste chains: climate change (CC) impacts, natural resources use and toxic impacts caused by hazardous substances. The two last mentioned were analysed only qualitatively. The results of the LCA show that the performances of the waste chains can be enhanced by reducing the landfilling of biodegradable matter and increasing the recycling of metals, plastics, paper and cardboard fractions.

The operational chain level analysis and the theory of value formation have been identified as emerging analysis techniques for waste stream research. The value formation technique was found to be very suitable for the WEEE and ELV waste stream, i.e. streams with high material value. Thorough value formation analyses have been performed for these streams showing the value potential of the materials that are currently not recovered in the conventional recycling process which was selected as a base case.

## 5.2 Development needs and opportunities

The key challenge for the waste management sector is to increase recycling as a way of reducing the overall use of natural resources. This calls for improved waste chain management with more efficient processes and technologies. Furthermore, product chain management, including life cycle impacts assessments, eco-design and analysis of future scenarios, facilitates increased recycling.

A challenge clearly identified in all the waste chain analyses is the lack of good quality data. There is a need for better quantity and quality analyses of the waste streams, and for tools to keep track of the different waste streams during processing. Research is needed to produce reliable data on the quantity, composition and quality of waste material flows both prior to and after sorting and treatment processes. This would enable better identification of the most important and most economically feasible raw material sources and reliable estimation of their potential.

In addition, there is a clear need for databases containing updated and reliable recycling process data which can be used in process, sustainability and business modelling, and as data for scenario analyses. One of the challenges is efficient material flow management and decision-making in multi-stakeholder waste chains.

The analysis of the operational chains shows that the current recycling processes based on the crushing of multi material flows and separation of materials from this mixed flow are not suitable for the recovery of low concentration valuables. Due to mixing with other materials, they are further diluted at various processing stages. The crushing and shredding technologies are energy-intensive, and originally developed for more homogeneous materials than mixed waste streams. The sustainability and efficiency of the processes could be improved by optimisation and better adaptation of these stages for waste materials. The development of crushing technologies on other sectors should also be followed.

In addition, the processes produce mixed residues which are only suitable for low-grade uses or landfill disposal. The amount of these residues should be minimised and their quality improved, in order to fulfil the requirements of stricter recycling targets and the landfill ban on organic waste.

Therefore, the high rate of mixed waste treatment can be seen as one of the main obstacles to increased utilisation of the material potential in all the waste chains studied. Through increasing on-site sorting and developing of automatic disassembly methods and other improved pre-separation methods as well as through increased implementation of mechanical sorting, the proportion of mixed waste may be reduced, thus enabling more efficient material recycling. Based on Climate Change impact analysis, the share of collection and pre-treatment seems to be small compared to the overall CC impacts. More sorting and pre-processing could be introduced to the chains in order to improve quality and increase the recovery of materials.

It was also noticed, that the quality of the product streams is degraded if impurities are not pre-separated, but mixed into the material streams during shredding and further processing. These contaminations should be removed, and if possible different fractions pre-separated at an early stage of the sorting and processing in order to improve the quality of the end product. Some examples of the materials which reduce the quality of product streams include gypsum board and insulation materials in construction waste, copper thread coils in vehicle motors, biowaste and aluminium in municipal and C&I waste. Treated wood, metals and PVC cause problems in the incineration process and reduce utilization possibilities for the ash, which is why they should be separated more efficiently.

In order to improve the material separation efficiency, identification, detection and separation technologies need to be further developed and adapted to the different stages of recycling processes, from pre-treatment to the quality control of the product. Improved identification and detection methods enable more efficient separation results and higher quality and value of recovered materials. The possibilities of technology transfer from other sectors should also be assessed. Especially important is e.g. the identification of different plastic types including black and dark plastics, as well as contaminations, such as chlorine, flame retardants and heavy metals. Also methods for better separation of mixed waste fractions are needed. For management of the whole treatment chain, real-time monitoring of different flows and on-line quality control of product streams are needed.

Increased recycling, incineration and the landfill ban of organic materials affect the quality of waste to be landfilled in future. They also enable new landfill concepts where landfills are turned into storage areas of unused materials. The effects of the changes to the materials disposed in future as well as landfill practices and concepts should also be studied.

## 5.3 Material flow specific development needs

In the future, finding technologies enabling the implementation of the requirements of the stricter waste legislation and future strategic targets is important. There is a clear need to find new economically viable solutions for recovering scarce materials from waste streams. This requires a new way of thinking for the treatment of the waste chains. To evaluate the economic viability and sustainability of potential recycling concepts, new integrated modelling concepts need to be developed. These can be based mainly on adaptation and integration of models used by other sectors.

The 70% material recycling of C&D waste in Finnish circumstances will become difficult to accomplish, which is why research on separation and recycling technologies for C&D waste should be of specific research interest in the future. There is a special need for new ways of recycling waste wood, but also for the development of recycling of smaller fractions, such as plastics, insulating materials, glass and waste gypsum.

The landfill ban of organic materials will create some new challenges; Besides the incineration of mixed household waste, new solutions for increased recovery of plastics and biowaste will be needed in order to follow the waste hierarchy and to implement the material recycling targets of the legislation. The potential for integrated utilisation of the same type of plastics from different sources should be further studied. The need to optimise the treatment processes by identifying and exploiting the synergies both inside and between waste chains also applies to other material streams and treatment processes. The opportunities for adding value to biowaste by combined material (e.g. nutrients, raw materials of chemicals and bioplastics) and energy recovery as well as integrated treatment with other waste streams, such as municipal and industrial sludges, agricultural waste, etc.

The stricter recycling targets of the ELV and WEEE require improvements both in collection and recovery efficiency, including minimisation and better recovery of shredder waste from ELV treatment. These chains also contain low concentration valuable materials, which are difficult to recover from the waste stream.

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# Appendix 1: Analysis reports produced during the project

*The analysis reports can be obtained upon request from the responsible research organisation.*

**Aalto University:**

- Maria Törn and Juha Kaila. Recycling and utilization methods and value chains for waste electrical and electronic equipment (WEEE). 36 p.
- Jukka Heiskanen, Juha Kaila and Hanna Vanhanen. Recycling and utilization methods and value chains for end-of-life vehicle (ELV). 46 p.
- Johanna Laaksonen and Juha Kaila. Recycling and utilization methods and value chains for commercial and industrial waste (C&I). 55 p.

**Finnish Environment Institute (SYKE):**

- Dahlbo, H., Jouttijärvi, T., Suoheimo, P., Retkin, R., Sorvari, J. & Myllymaa T. 2012. LCA and BAT assessments of waste recovery and management value chains – NeReMa-project. 54 p.
- Mattila, T., Sironen, S. & Lähtinen, K. 2012. Environmental life cycle costing of new waste recycling facilities. 14 p.
- Saramäki, K. 2012. Strategies, policies and legislation affecting the waste management sector in the future. 20 p.

**Lappeenranta University of Technology (LUT):**

- Jouni Havukainen. Technical analysis: Waste to Energy. 45 p.

**Technical Research Centre of Finland (VTT):**

- Nina Teirasvuo. Identification, Monitoring and Separation Methods. 74 p.

*Construction and demolition waste:*

- John Bachér. Applications and requirements of C&D waste. 12 p.
- John Bachér. Material flow- and technical analysis report of C&D-waste. 37 p.
- Johannes Jermakka. Construction and Demolition waste stream analysis. 8 p.
- Malin Meinander. C&D waste market analysis. 20 p.
- Peter Nielsen. Overview of the construction and demolition waste management in the Flanders region in Belgium. 24 p.
- Hannele Kuosa. Reuse of recycled aggregates and other C&D wastes. 69 p.
- Hironori Nagai. Japan Concrete Recycling: Past, Present and Future. 33 p.
- Hironori Nagai. Construction and Demolition Waste Recycling in Japan. 36 p.

*Municipal solid waste:*

- John Bachér. Applications and requirements of MSW. 17 p.
- John Bachér. Material flow- and technical analysis report of MSW. 59 p.
- Johannes Jermakka. Municipal solid waste stream analysis. 33 p.
- Malin Meinander. MSW waste market analysis. 35 p.
- Malin Meinander. MSW cost analysis. 16 p.

# Appendix 2: Methodology of MFA and building it with STAN 2.0 software

Material flow analysis (MFA) is a descriptive approach which provides snapshots of parts of the physical economy. MFA refers to the analysis of the throughput of process chain comprising extraction or harvest, chemical transformation, manufacturing, consumption, recycling and disposal of materials (Brigenzu et al., 2002). The analysis is based on physical units quantifying the inputs and outputs of previously mentioned processes. There are different types of MFAs depending on the angle of focus. Some MFAs are focused on the material or the substance flow, while others are focused on a certain area where a descriptive flow map has been performed.

**System boundaries**
The system boundaries have to be carefully chosen since they determine the scope of the analysis. The model can have different types of boundaries depending on the focusing level. For example, MFA for waste can have boundaries for the whole waste chain and sub-boundaries for a certain recycling factory within the waste chain.

**Building the model**
After the system boundaries have been set, the model of the MFA can be built. The model assumes that the difference between inputs and outputs is 0 if there is no stock in the process. In addition, the model can calculate concentrations in different flows at which time the mass is multiplied with the concentration of a certain substance. The model can be built at many levels, and sub-systems can be built within processes.

**System level**
The system level is the holistic description of the model. This level describes the material flows over the whole material chain which is examined. It may include flows, processes (which can consist of sub-processes) and stocks. In Figure A the system level of the treatment of municipal solid waste (MSW) is presented.

**Process level (sub-system)**
In the STAN 2.0 software sub-systems can be built inside a process. This provides a possibility to model the inner structure of a process in more detail (Cencic, 2008). Sub-system must have the same amount of inputs and outputs as the process (box) in the upper system level. In Figure B the Splitting plant from Figure A is opened as a sub-system.

Comparing Figures A and B, it can be seen that in the input and output flows for the sub-system in Figure B are the same as for the Splitting plant process box.

**Input data and result display**

A critical section of MFA is the data which is fed to the model which then calculates the material flows. The data should be carefully chosen since the model does not editorialize at all the numbers which are entered into the model. Data can be entered manually with units and data uncertainties for different data layers and time periods (Cencic, 2008). The uncertainties are extended over the process chain by data reconciliation. In Figure C the data has been entered into the model which was presented in Figure A.

The STAN software presents the flows in form of Sankey diagrams on the drawing area. Thereby the width of an arrow is displayed as proportional to its mass flow value (Cencic, 2008). In addition, the analysis can be performed for different materials/concentrations in the feed such as metals. In this case, the flow of metals is displayed at the process drawings in the same way as the MSW (Figure C).

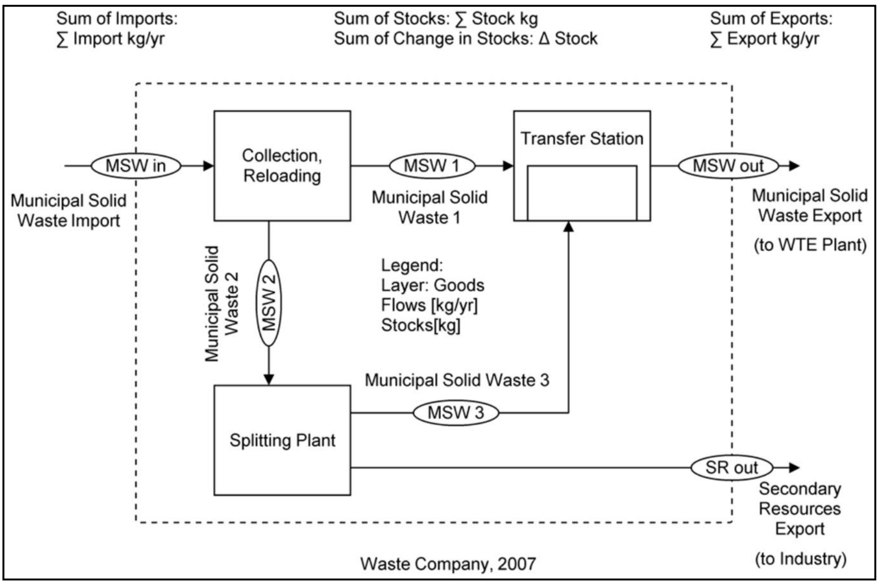


**Figure A**. Model of the system. (Cencic, 2008)

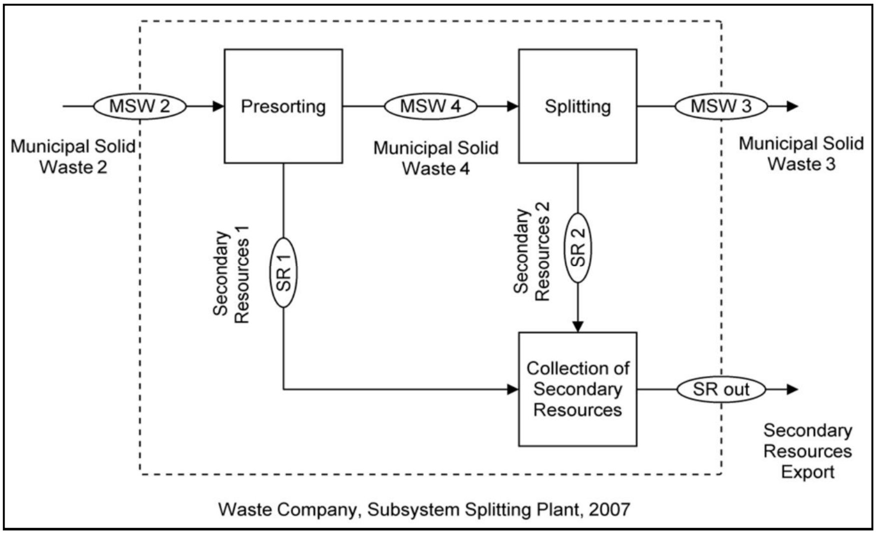


**Figure B.** Model of the subsystem of the splitting plant from Figure A. (Cencic, 2008)

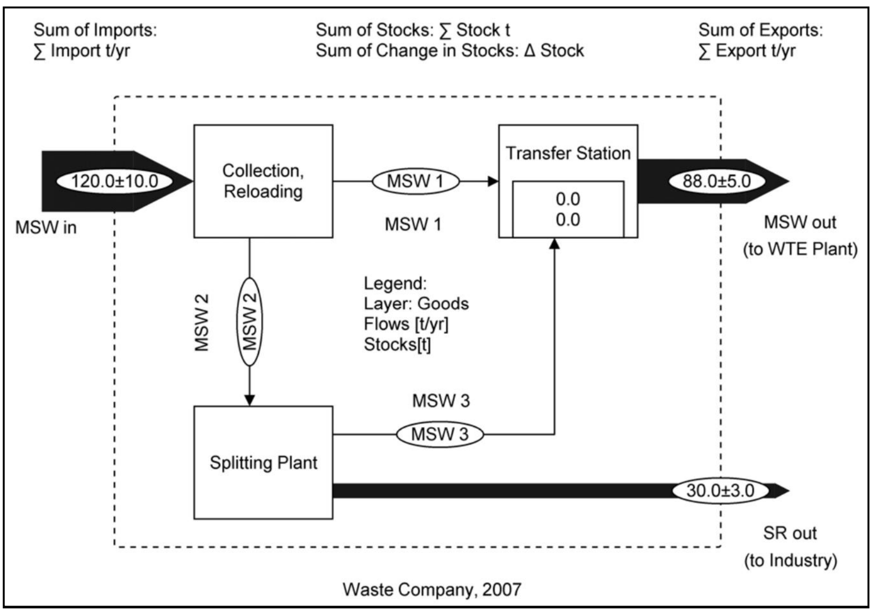


**Figure C**. Model of the system including data. (Cencic, 2008)

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# Appendix 3: Detailed C&D waste chain

Construction and demolition waste (C&D waste) is all waste other than regular household waste produced at a construction site (Finnish Legislation 295/1997). It includes neither waste reused directly on-site without any processing nor waste generated by the construction industry off-site (Perälä & Nippala, 1998). A typical feature of C & D waste is that it is not continuously generated, and its characteristics varies due to the site specific situation. C&D waste is commonly very heterogeneous, with a high mineral composition and a low content of combustible and biologically degradable matter. (Monier et al., 2011)

The C&D waste generators are mainly construction and demolition companies, as small construction sites (private houses) are not covered by the C&D waste legislation which has a waste volume limit at 5 t. Waste producers are obliged to provide for appropriate management of the waste according to Finnish waste legislation. The role of the municipalities is to guide and govern the sorting and treatment of C&D waste.

Figure A illustrates the C&D waste chain for recycling. The C&D waste is commonly collected and transported to treatment facilities directly from the construction site by the contractor. The quality of the waste is influenced by the performance/specifications/requirements of selective demolition. The further processing generally includes only mechanical processing and further refining or utilization as material or as fuel in energy production. At all stages some rejects are generated.

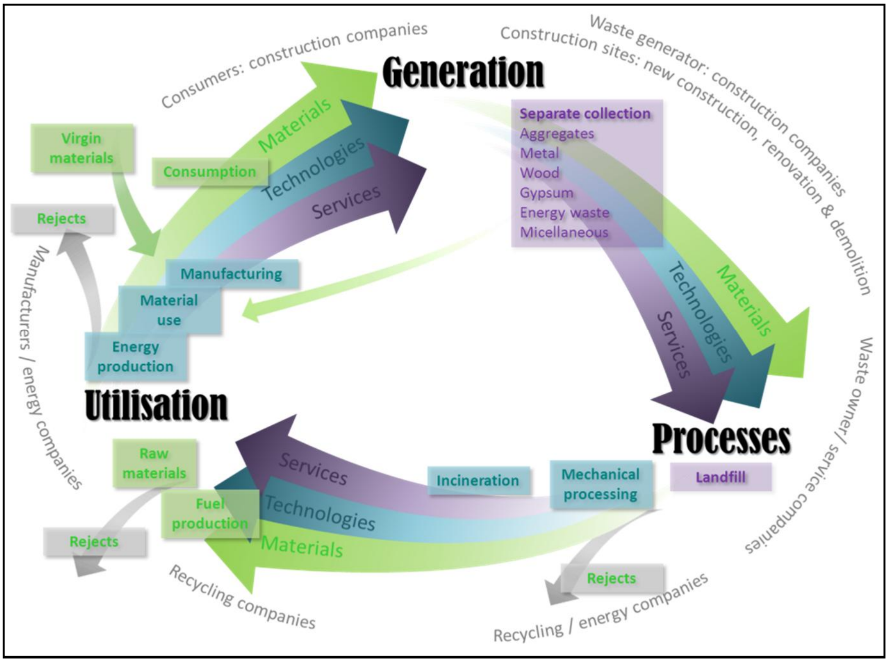


**Figure A.** The C&D waste cycle containing generation, processing and utilisation.

C&D wastes are generated at three types of construction sites: renovation (27%), demolition (57%) and construction (16%) (Environment, 2009). Each of these sites produces waste with different composition and characteristics. The waste streams of construction sites are mostly clean material surpluses which are not mixed or contaminated. Demolition and renovation waste, on the other hand, is mixed and contaminated and thus also more difficult to recover. (Monier et al., 2011)

- The waste produced at construction sites can be divided into production waste (losses, left overs and side materials) and packaging waste. Since material efficiency affects project costs, the minimization of production waste is often a priority for the construction site, thus reducing waste generation. (Hurme, 2007.)
- On the renovation site, materials or components such as windows etc. are dismantled separately and mainly collected for recycling. Dismantling is done mainly by human labour inside the building. (Henriks & Janssen, 2001.)
- Demolition can be implemented as selective, partially selective or non-selective; partially selective demolition is used in Finland. Selective demolition is the dismantling of the building using non-destructive mechanical tools to separate materials for reusing and recycling. The pro-

duced fractions are clean from hazardous contaminants and materials that cannot be recycled (Kourmpanis et al., 2008.)

In Finland it is estimated that approximately 2 Mt of C&D waste generated from house construction sites in 2007. Approximately 38% was recycled as material, 35% recovered as energy, 6% utilized at landfills and 21% landfilled. Figure B presents the estimations made of construction, rehabilitation and demolition waste produced in Finland in 1990–1997 and 2000–2004. The Finnish National Waste Plan for 2016 sets the target to 70% reuse, recycling and recovery. However, the EU Waste Framework Directive (2008/98/EC) requires a 70% reuse and recycling rate by 2020, excluding energy recovery (EU, 2008). In northern Europe wood is the main construction material, whereas brick and concrete are dominating elsewhere. As energy recovery is not seen as recycling in the EU waste framework directive, Finland will have some problems achieving the 70% recycling rate.

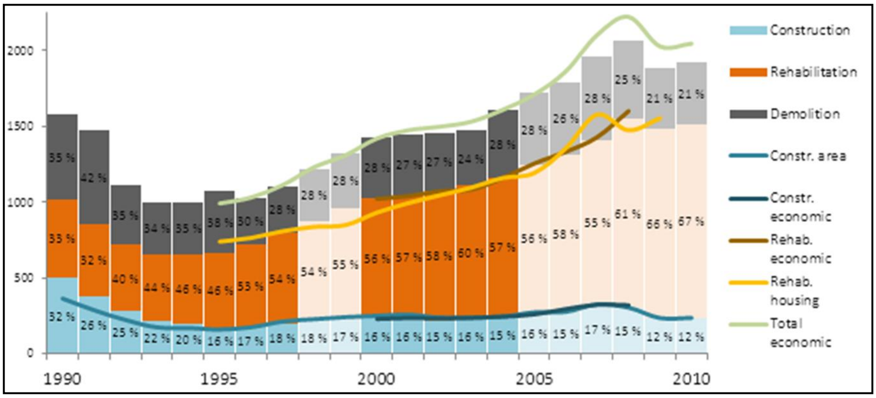


**Figure B.** Estimations of C&D waste from construction, renovation and demolition activities in Finland [1000 t/a] 1990–2010 (Perälä et al., 2006; Perälä, 1998; Statistics Finland 2011; Eurostat 2010).

When recycling construction and demolition waste, the waste must be thoroughly separated either through on-site sorting or in mechanical sorting facilities (Zhao et al., 2010). On-site sorting maintains a better waste quality than mechanical sorting. On-site sorting of C&D waste is mandatory in Finland, unless circumstances make it impossible to implement or it is economically much more expensive than other alternatives.

In most cases the waste fractions require some kind of processing to recover economically profitable materials. Mechanical processing is the most common treatment method. The processing is usually implemented sequentially: common process steps are size reduction, size controlling and separation/enrichment of desired material. The processing can be put into practice either on the work site (on-site) or at a recycling centre (off-site).

- Metals makes up slightly below 15% of the C&D-waste, of which approximately 75% is sorted for recycling (Perälä et al., 2006). Furthermore, metals separated from the other waste streams are collected for metal recycling; altogether approximately 91% of the C&D waste metals are recovered. The majority of the scrap metals are clean fractions, which are sold directly to recyclers. The mixed metals need mechanical sorting before utilisation; they are first shredded, after which magnetic separators remove iron (98%). Then a density separation removes non-ferrous metals such as copper, aluminium and stainless steel (RST). This fraction is around 1% of the total input; the remaining 1% is reject material. Metals are easy to recycle as material together with other scrap metal streams. The quality of metal fraction is vital for the further refining processing in order to minimize the possible damages which might occur when too much impurities exists in the feed.
- Approximately 35% of the C&D waste is concrete, of which approximately 70% is sorted for recycling (Uusiouutiset, 2008). Furthermore, concrete separated from the mixed waste is collected for recycling; altogether approximately 84% of the C&D waste concrete is recovered. Concrete is made from cement, water and aggregates (sand and gravel or crushed stone); reinforced concrete consists of steel as well. Ceramic waste is quite similar to concrete waste, although it is a homogeneous material without steel reinforcement; ceramic waste is commonly treated as aggregates. Bricks and tiles are very durable and can be reused after demolition. Reuse of tiles is used only for the “retro” and green image, and is not a common practise in Finland, as reuse is more expensive than utilisation of virgin tiles.
    - The mineral waste is recycled into aggregates by crushing and sieving the concrete into suitable sized fractions and removing impurities (0.5%) and steel (approximately 1.5%). The aggregates can be used in earthworks and as aggregates in e.g. concrete production although the cement needs to be virgin. The main barrier to the recycling of the mineral fraction of C&D waste is the easy and cheap access to virgin raw materials. (Monier et al., 2011)
- Gypsum is used in non-bearing structures for interior surface materials. Construction waste gypsum is clean and can be recycled as a material, but demolition and renovation waste is harder to recycle, as the plasterboards has more contaminants, such as paint, nails, screws, insulation, and wallpaper. During the recovery process, the paper is removed and the gypsum crushed into a powder, which is sent to the plasterboard manufacturer. The paper (approximately 6%) is commonly recovered as energy. Paper contaminations in the gypsum fraction create poor quality plasterboard, why high recycling rates are impossible.
- The wood fraction makes up approximately 35% of the C&D-waste, of which approximately 70% is sorted for recycling. Furthermore, wood sep-

arated from the mixed waste is collected for recycling; altogether approximately 88% of the C&D waste wood is recovered. The C&D wood waste is quite a heterogeneous fraction; construction waste is quite clean containing mainly timber, while renovation and demolition is contaminated by coating, such as paint and preservatives. The wood is first shredded into smaller particle size then magnetic separation removes nails and angle irons. The wood waste is commonly contaminated, thus energy recovery is the only suitable alternative for wood treatment. (Alakangas & Wiik, 2008)

- Energy waste contains mainly plastics and fibres such as paper which have rather high calorific value. The processing to Solid Recovered Fuel (SRF) is commonly screening, magnetic separation, shredding, eddy current separation and air classification. The product is used as a fuel in energy production.
- Mixed waste makes up approximately 40% of the C&D waste. Of this approximately 50% is landfilled and 50% recovered as material or energy. Large pieces of rocks, stones, wood and reject (PVC-plastic, roofing felt etc.) are removed manually. The large stones are processed into aggregates, while the wood is used in energy utilization and the reject is landfilled. After the manual sorting, the mixed waste is shredded. Then a magnetic separator removes the iron (approximately 7.5%), after which the waste stream is sieved to separate fines (approximately 30%) to be used in landfill constructions. Non-magnetic metals (Al and Cu) are removed from the large fraction using eddy current. All metals are recycled. Finally, an air separation or another density based separation produces a high calorific value fraction (light) and a low calorific value fraction (heavy). The light fraction is used for energy utilisation as REF, while the heavy fraction is landfilled.

**Future waste generation scenarios**

Figure B (CD estimations) indicates that rehabilitation activities have grown while construction and demolition activities have been rather stable since 1995. It can be assumed on the basis of the age distribution of the Finnish housing stock that rehabilitation activities will still grow (Jermakka, 2011). Rehabilitation activities generate more wood and metals, but less minerals than the other C&D activities. On the other hand, large apartment buildings from the 1960s and 1970s are getting older, and increased demolition might generate more minerals (Kojo & Lilja, 2011). Table A present, the current composition of C&D-waste, as well as estimations for two future scenarios.

- Scenario 1 presents increased renovation while demolition remains stable. The wood fraction would increase, as well as metal content, while minerals would decrease.

- Scenario 2 presents increased demolition while renovation remains stable. The mineral fraction would increase, while wood and metal would decrease.

**Table A.** The compositions of current state and two scenarios.

| | Current | Scenario 1 | Scenario 2 |
|---|---|---|---|
| **Metals%** | 13.5 | 15 | 10 |
| **Minerals & Concrete%** | 35.0 | 20 | 50 |
| **Wood%** | 36.0 | 45 | 20 |
| **Other%** | 15.5 | 20 | 20 |

***C&D waste management in Europe***

*The C&D waste generation of the EU member countries varies between 0.04 t/cap in Latvia to 5.9 t/cap in Luxembourg with an average 1.09 t/cap. At the European level there are major differences in what is actually reported as CDW, resulting in practically non-comparable statistics. (Eionet, 2009; Eurostat, 2010)*

*The Waste Framework Directive (2008/98/EC) emphasises the waste hierarchy. The directive requires EU member states by 2020 to achieve a 70% (weight) preparation rate for reuse, recycling and material recovery, but excluding energy recovery. The directive aims at unifying the waste and recycling definitions throughout the union, allowing for similar regulation in all member countries. (EU, 2008)*

*The average recycling rate for C&D waste in the EU is 46 %, although the differences are significant between member countries. There are also major differences at the European level in how recycling is actually reported. Of the EU member countries, 6 countries report recycling rates exceeding the target of the directive, 3 countries report recycling rates of 60–70%, 4 countries report recycling rates of 40–60%, and 8 countries report recycling rates lower than 40%. (Monier et al., 2011)*

*For many years the Flanders region (Belgium) has been a leading player in the management of construction and demolition (C&D) waste due clear governmental initiatives providing statistical information about waste amount and quality, promoting selective demolition with standardised specifications, introducing certificates for aggregates, clear environmental specifications for recycling.*

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# Appendix 4: Detailed C&I waste chain

Commercial and Industrial waste (C&I) is the waste produced by institutions, commerce and industry, excluding production and process waste, and is comparable to municipal solid waste (MSW). It is often collected and treated, and usually reported together with MSW. C&I waste is very similar to MSW, but the fractions, especially plastics and metals, can be cleaner than the same fractions in MSW. The quantities of similar materials can also be larger than in MSW, which makes some of the fractions good for recycling.

The composition of commercial and industrial waste varies a great deal according to the origin of the waste. The main producers of C&I waste are offices, schools, restaurants, hotels, hospitals and retail stores. The main fractions of commercial waste are similar to those of municipal solid waste, but the shares of different fractions are different. The main flows and stakeholders of C&I waste chain are presented in Figure A.

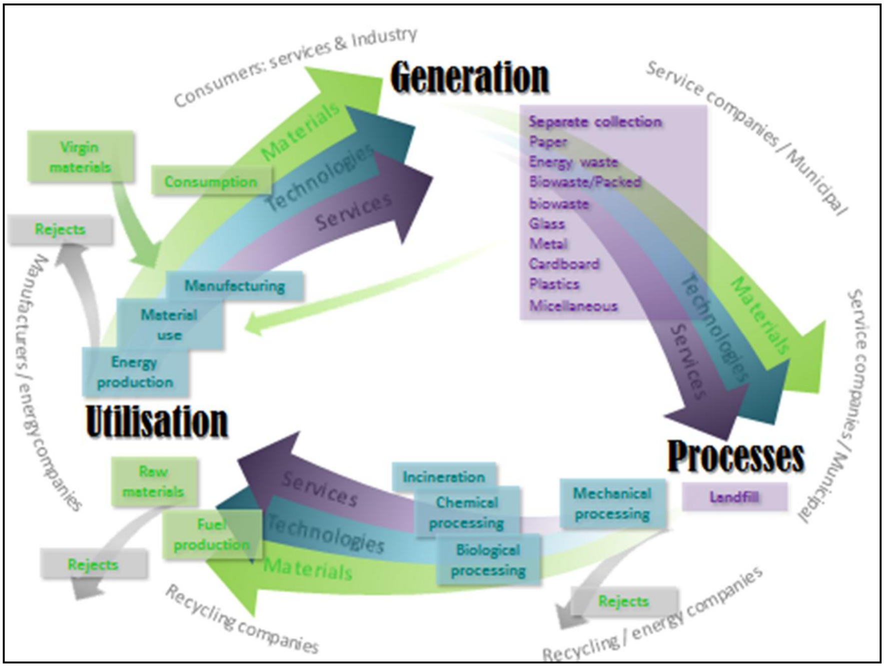


**Figure A.** Primary flows and stakeholders in C&I waste management life cycle.

Different entities produce and recycle different fractions. Recyclables from C&I consist of plastics, paper, cardboard, metals, and glass, which are suitable for recycling and reuse. Plastics, paper and cardboard are also suitable for incineration, but this is not a preferred option for handling waste according to the EU waste hierarchy (EU, 2008). The waste which is not source-separated as a pure material fraction ends up usually in mixed waste or is source-separated as an energy fraction or biowaste.

In the C&I sector one of the most economically and materially interesting waste producer groups is retail and wholesale. They produce large amounts of packaging waste, which is clean and consistent and easy to use for recycling. Retail stores alone use around 60 000 tons of packaging materials per year, more than half of it wood from pallets (FGTA, 2003). According to Finnish Grocery Trade Association (FGTA, 2003), the greatest waste fractions from retail stores are OCC 35%, energy fraction 40%, and biowaste 15%.

In this research, an estimate was made of C&I waste generation and general material flows in Finland. The estimation is based on statistics of MSW and C&I waste. It has also to be remembered that the statistics are estimations and not accurate numbers. There are no general statistics in Finland concerning the generation of C&I waste, and therefore MSW numbers were applied in some cases. The energy fraction and mixed waste were not considered as generated fractions in this research. Waste generated consists of material fractions, and the goal in this research was to make a Material Flow Analysis (MFA) of all the significant materials that C&I sector generates. The approach was to calculate the amount of material generated in each material category and then of these the share that was source-separated. The remainder of each material goes to mixed waste. From all these fractions it was estimated how much was ending up to landfill, recycling and incineration. This differs from the typical approach to waste management fractions, but in order to be able to track the flows completely, this kind of methodological approach is needed.

**Key actors**

The municipalities organize most of the municipal waste management and waste collection in Finland. Practically all waste collection and transport is done by private companies either on municipal contracts or direct contracts with waste producers. The regulations by which waste fractions are collected and how the waste management is handled, differ according to the municipality. Some municipal waste companies work in co-operation with the private recycling companies. (JLY, 2011.)

In Finland, the private companies as waste producers, are responsible to organize their own waste management. If the companies are located, for example, in properties with households, the municipal waste management usually takes care of the company's waste management, and the company pays the costs of waste management for the property owners. (Kaila et al., 2006)

Usually the waste producer invites different waste management companies to tender and chooses one according to price and service. Also, the reputation of a bidder may affect the selection process. In some cases if the organization is part of a chain, for example a retail store, the chain may organize the bidding process to help the stores. In this way, the stores may get a better offer because the waste management company gets more volume (Salminen, 2011; Koivuniemi, et al., 2012; Pelin, 2012; Koivisto, 2012).

Depending on the company and the types of waste produced, the effects of waste legislation are different. The new waste legislation comes into force on May 1, 2012. The biggest effects of the new waste legislation in C&I sector are mainly caused by the restriction on delivering biowaste to landfills (Salminen, 2011; Pelin, 2012; Koivuniemi & Rintala, 2012). The target of the new waste legislation is to increase recycling, but incineration probably also increases.

Another significant factor affecting C&I waste management is EU regulation concerning animal by-products (Finnish Food Safety Authority). The by-product regulation in particular affects waste management in retail stores, because the waste has to be treated in Evira-approved facilities. Not all the biowaste comes under the by-product law, but because the facilities in the stores are usually limited all the biowaste is usually collected in the same bins and needs to be treated according to the by-product regulation (Salminen, 2011). Depending on the case, this may increase the costs especially because of the transportation distances and labour costs. (Lilja & Liukkonen, 2008).

**Recycling technologies, systems and services**

Recycling depends on the facility that produces the waste, but in general the recyclables follow the same flow. Recyclable fractions (biowaste, paper and cardboard, metal, glass, plastic and wood) are source-separated, collected and transported to the pre-treatment centers. From collection the fractions continue on to processing, refining and finally to markets as materials or as new products. The process is usually the same as with MSW, except that biowaste from retail stores comes under by-product regulations. Also, some recyclables such as plastics are of better quality than plastic from MSW and therefore are recycled more.

Some proportion of recyclables are also used in energy production. REF (Recovered fuel) can be made from mixed waste or from source-separated energy waste. Without pre-treatment, mixed waste can be transported to landfilling or to waste incineration, which is usually grate incineration without pre-treatment. Figure B shows the estimated generation, recycling and disposal of C&I fractions. Figure C illustrates the composition of incinerated waste.

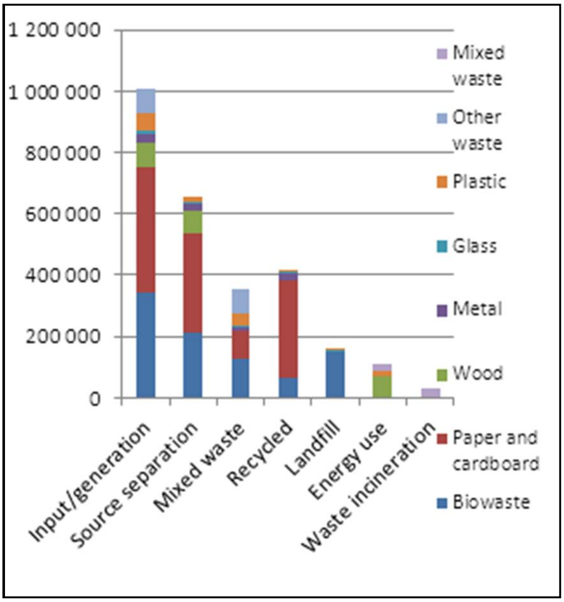


**Figure B.** C&I total generation, recycling, reuse and incineration [t/a].

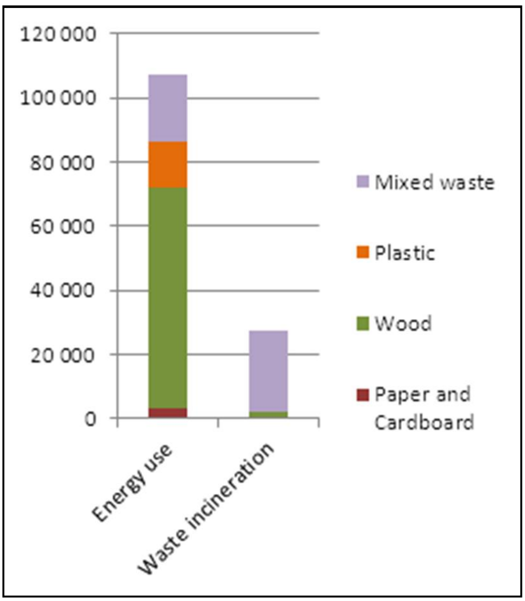


**Figure C.** Estimated generation of energy-recovered waste and waste incineration [t/a].

**Waste generation in Finland**

For this research, the data was collected from three main sources and combined. The waste statistics of Statistics Finland were used, also the statistics provided by producers' responsibility organizations and statistics from HSY's Petra service. One significant problem was noticeable; statistics are not coherent and it is difficult to make comparisons.

Helsinki Region Environmental Services Authority (HSY) has statistics of service sector waste generation, which is called the Petra service (Petra, 2011). These numbers were used when making the material flow analysis (MFA) of C&I waste generation. This data was the best available for estimating the share of C&I from MSW. The statistics are compiled from the capital area's service sector, so they are not totally applicable to the whole Finland, but some approximation can be made using them. The statistics for personnel working in the field during 2008 were from Statistics Finland (Statistics Finland, 2008a).

The estimated total waste generation of the C&I sector in one year is about 1 084 000 t (Jokinen, 2005; Petra, 2011; Statistics Finland, 2008a; 2008b).

JLY (2011) estimates that the share of C&I waste of the total annual MSW production is about 40%. If the estimated total production is compared to the total MSW production in Finland in 2008 (2 768 000 t/a), it can be seen that the share of C&I is 39%, which corresponds with the estimation of JLY (Statistics Finland, 2008b). Figure D presents the total generation of waste from the C&I sector. The amount is divided into different factions and by source separation. It is estimated that about 330 000 t of waste ends up in mixed waste. Figure E presents the amounts of different ways of disposing of mixed waste.

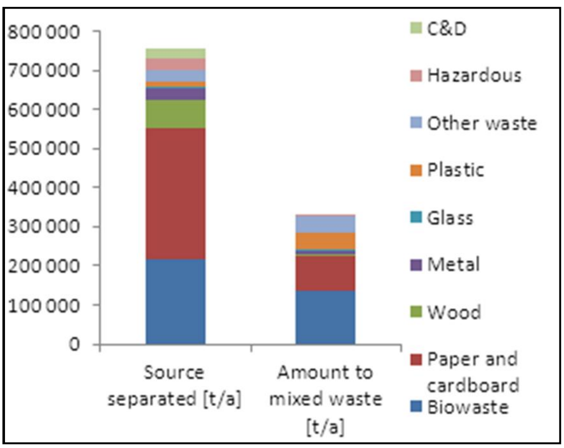


**Figure D.** Estimated C&I waste generation divided into source separation and mixed waste [t/a].

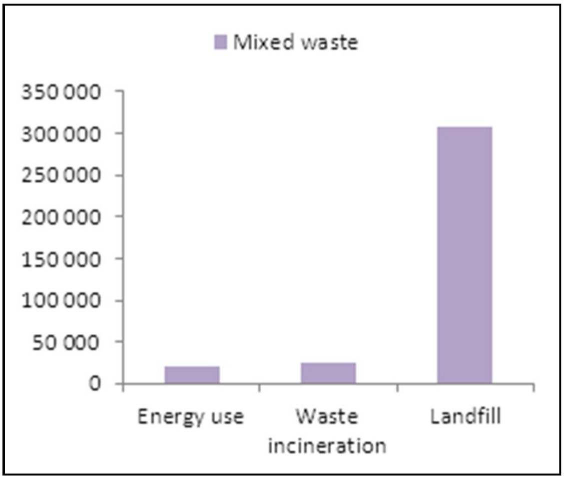


**Figure E.** Estimated disposal of mixed waste [t/a].

**Waste generation in Europe/in some selected countries**

The shares of different C&I waste fractions in Finland, Norway and Ireland are compared in Figure F. The values for Finland were calculated according to earlier explanations, and values of Norway and Ireland were taken from literature. As can be seen, the biggest fraction in every country is Paper and cardboard. Biowaste also has a big share in every country, but in Norway it is the smallest. Construction and Demolition waste (C&D) was listed only in Finland, which has a minor effect on the share of other fractions in Finland. In general the main distribution in different countries is quite similar.

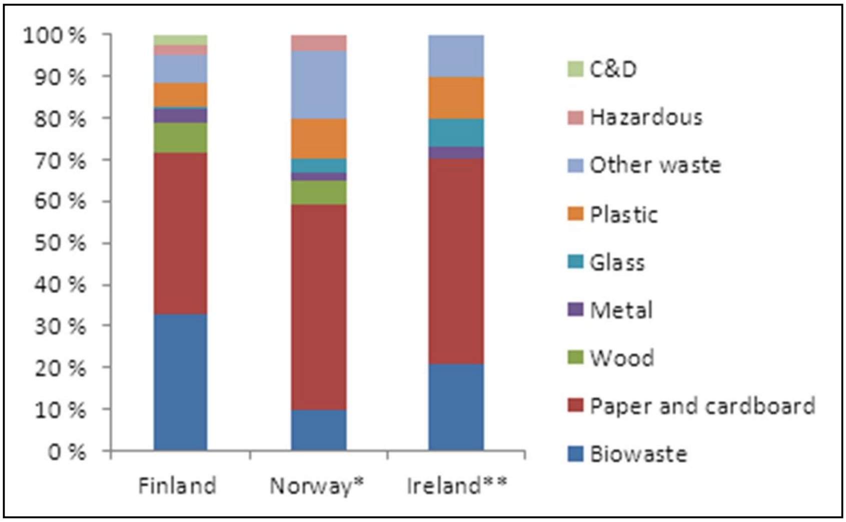


**Figure F.** Share of waste generation in C&I sector in 3 countries (combination of sources in Christensen et al., 2010; original sources: Skullerud, & Stave, 2002; EPA IRL, 2003)

Waste generation in the C&I sector is strongly linked to the total sales of the company, so the generation follows the general economic situation. In the future of C&I waste the main differences are probably going to be in end use. For example. biofuel production is a growing trend in Finland and in the future biowaste from MSW and C&I will be probably also used in that area (Kuittinen & Huttunen, 2009).

New waste legislation cuts the amount of biowaste ending up in landfill and increases the need for proper treatment facilities. Also, demand for increasing the recycling and reuse rates of waste increases the need for new treatment methods. Because main recyclables such as paper and cardboard are already well recycled in Finland, the main increase in recycling is probably in plastics and biowaste. Probably the main treatment method for waste that is not easily recycled is incineration.

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# Appendix 5: Detailed MSW chain

MSW (Municipal Solid Waste) covers waste from households as well as similar waste from commerce and trade, garden waste, street sweepings and the contents of litter containers (Finnish Legislation 1129/2001; OECD, 2010). MSW treatment consists of seven individual process chains for the separate waste fractions (mixed (including plastics), metals, glass, paper, cardboard, bio, wood and REF/energy). These fractions can be partly mixed together or separated, depending on the waste management system. Sorting is assumed to be carried out in households or at sorting stations.

Management of MSW is commonly the responsibility of the municipalities; this includes collection and treatment as well as administrative duties and monitoring. The customers of MSW management are mainly households and property owners. The waste producer is seen as responsible for the waste, and property owners must organise a waste collection point enabling separate collection of certain waste fractions. In Finland, the waste management services are highly outsourced; private environmental management companies cover a wide range of services, such as waste collection and transport, utilisation, recycling and treatment, as well as customer and advisory services, reporting, and invoicing. Figure A illustrates the MSW waste chain for recycling. The MSW management chain consists of three main steps: generation (including collection and transport), processing (including disposal), as well as utilisation of the recycled materials. The produced MSW has to be collected (possible separate collection) and stored before transport to further processing or final disposal. The further processing generally includes mechanical and/or biological processing and further refining or utilization as material or as fuel in energy production. In all steps some rejects are generated.

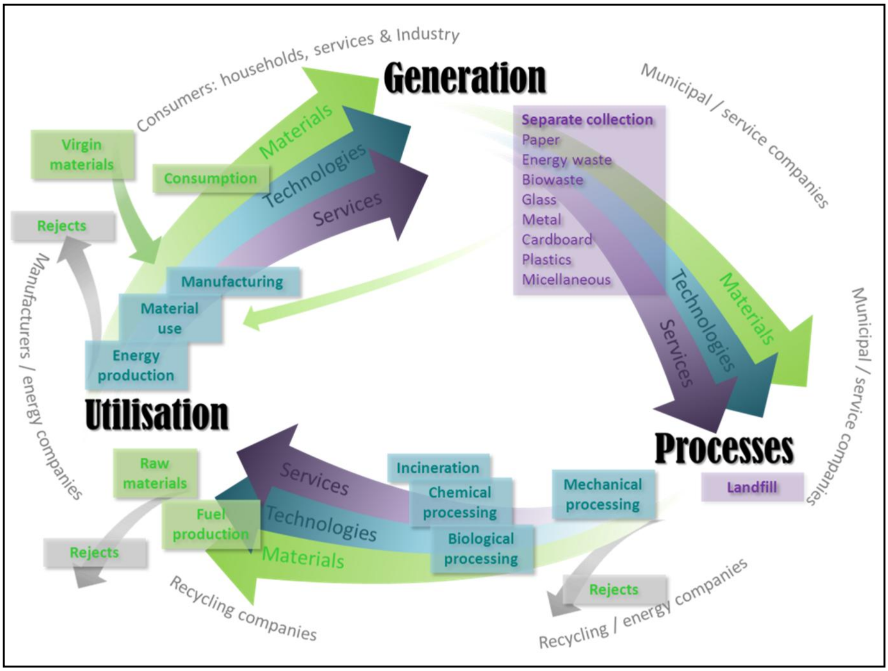



**Figure A.** The MSW cycle containing generation, processing and utilisation.

The MSW generation of a nation is commonly interconnected to its wealth; as a country develops, its waste generation increases, to slowly decrease when a certain level of prosperity is reached. As illustrated in Figure B, these statistics for Finland show that there has been a clear trend towards coupling of economy and waste production. In Finland, the production of municipal waste has increased over the last 30 years following economic trends; an increase in GDP shows a clear increase in waste, and economic downturns can be seen as clear drops in MSW production. (YTV, 2008; Troschinetz & Mihelcic, 2009)

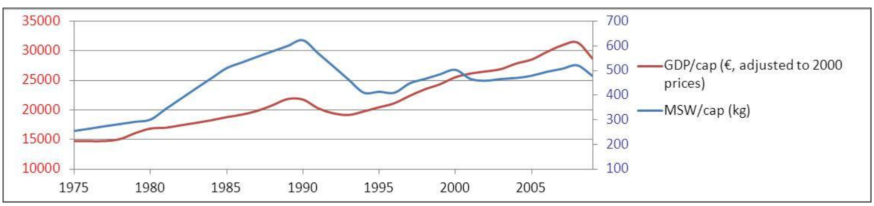



**Figure B.** The interconnection between MSW and GDP in Finland during the years 1975–2009 (YTV, 2008; Statistics Finland 2011a; 2011b).

The average annual MSW generation per capita in Finland is approximately 500 kg, of which household waste makes up approximately 60%, and C&I the remaining 40%. The largest MSW fractions in 2008 were mixed waste (59%), paper waste (14%), biowaste (11%), wood waste (3%), energy waste (3%) and glass waste (3%). Figure C presents the annual municipal waste production in Finland for the last reported years. MSW treatment in Finland is still based mainly on landfilling of mixed waste, although paper, glass and metals are rather efficiently separated and recycled. Biowaste separation is rather common and steadily increasing. During the past, a decrease in landfilling and an increase in recycling and especially incineration has been seen. (Statistics Finland, 2011a; Espo, 2011)

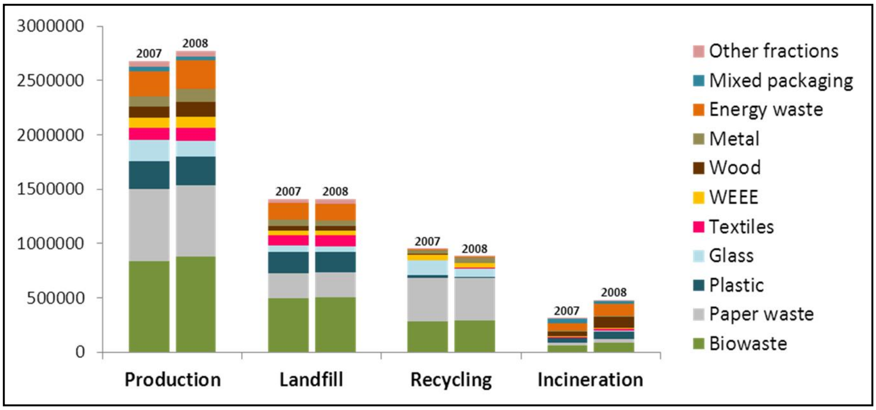



**Figure C.** Total municipal waste collected in Finland 2007–2008 [t/a] (Statistics Finland, 2011a; Espo 2011).

**Recycling technologies, systems and services**

There are alternative collection applications for the collection and transport of waste. Waste is mainly transported by different type of vehicles, although over shorter distances it can be transported in pipelines. These automated waste collection systems are not yet common. The collection points for different fractions can be located at drop-off stations or at the properties' waste collection points (kerbside collection). The collection system greatly affects operational costs but also recycling efficiency, as kerbside collection is more expensive but facilitates on-site sorting. (Kogler, 2007.)

**Table A.** MSW collection systems.

| Collection | Kerbside | Drop-off |
|---|---|---|
| Mixed | X | X |
| Paper | X | |
| Cardboard | X | X |
| Glass | X | X |
| Metals | X | X |
| Bio-waste | X | |
| Energy waste | X | X |
| Wood | | X |
| Hazardous waste | | X |

MSW processing consists mainly of mechanical unit processes, including size reduction, size control and mechanical separation processes. The use of monitoring and detection technologies for the identification of various waste fractions and impurities or for quality control of produced materials is still relatively unusual. Most of the waste fractions have quality requirements, as contaminations can be bad for the further processes e.g. damaging machinery or lowering the quality of the product.

- Metals make up for approximately 4% of the MSW, of which approximately 50% is sorted for recycling. Separately collected metals are shredded and fed into magnetic separation, where approximately 51% (mainly iron) of the feed is removed. The remaining metals are separated based on their densities. Aluminium makes up around 13% and other metals comprise approximately 28% of the input. The remaining 8% is rejects. Metal scrap is the commercially most important waste stream. It can be melted down and reused to produce new metal products, as the material will not degrade during the recycling process. The metal industry has quality requirements for scrap metals, as the quality is vital for the processing.
- Glass makes up approximately 5% of the MSW, of which approximately 60% is sorted for recycling. The glass fraction is first shredded and then sorted by colour (55% green, 20% dead leaf, 20% transparent and 5%brown). In theory glass can be recycled forever whilst retaining its chemical and physical properties. However, contaminations prevent glass from being recycled in glass production, which is why glass scrap is mainly recycled as e.g. glass wool and foam glass.
- Paper and cardboard makes up approximately 25% of the MSW, of which approximately 60% is sorted for recycling. Paper and cardboard are recycled either as raw materials for paper and cardboard production or as a fuel in energy production.

- The separately collected paper is first mixed with water producing a pulp, which is deinked using flotation, producing approximately 20% rejects of inks and other impurities. The rejects are incinerated. The pulp is washed and precipitated before recycling. Approximately 52% of the recycled paper is utilized in paper production.
- The collected cardboard and fluid packages are shredded and the fibre is separated. The reject (5%) consists of aluminium, plastic and other impurities, and is incinerated. Approximately 52% of the recycled cardboard is utilized in cardboard production.
- Organic waste (mainly food waste but also wood, paper, cardboard, plastics, textiles etc.) makes up approximately 35% of the MSW, which – when landfilled – decompose, generating greenhouse gases such as carbon dioxide ($CO_2$) and methane ($CH_4$). Treatment of organic waste reduces greenhouse gas emissions and facilitates recycling. Organic waste can be treated either through composting or through anaerobic digestion. The product can be used as a fertiliser or soil amendment.
    - Composting refers to a biodegradation process in aerobic conditions.
    - Anaerobic digestion is a multi-step process where microbes break up organic matter, forming methane which can be used as a fuel.
- Wood makes up approximately 5% of MSW, of which approximately 64% is sorted for recycling. The collected wood is shredded, after which it is utilized as energy (a minor part of the wood is used in material recycling).
- Approximately 7% of MSW is processed to produce REF, which can include, among other things, mixed MSW and separately collected energy waste. REF is used for energy utilization. The feed is shredded and the magnetic metals are separated from the feed using a magnetic separator. Then the waste stream is sieved and the larger fraction (appr. 55%) is further processed with air separation. The light fraction (appr. 50% of total input) is finally fed into an eddy current which separates aluminium (appr. 0,5% of total input) from the light fraction to further refine the REF. (See Figure D)

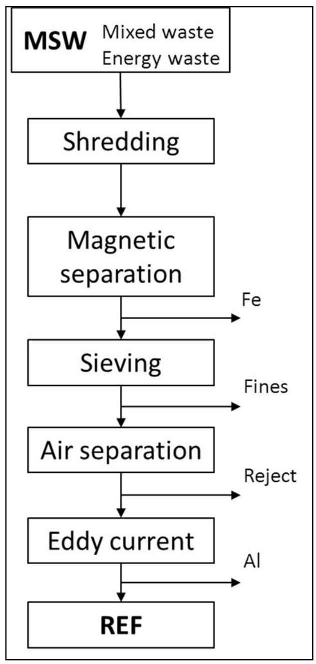
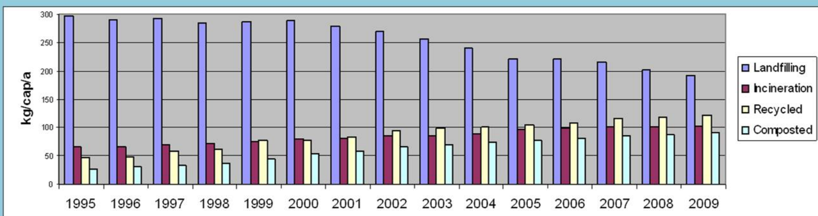



**Figure D.** Flow sheet of REF production

***Waste generation in Europe***

*European municipal waste has previously mainly been landfilled, but recovey of it is increasing. Of the total waste generated in the EU in 2009, 38% was landfilled, 24% was recycled, 18 % was composted and 20 % incinerated (with or without energy recovery). However, there are substantial differences between countries and regions; Bulgaria had 100 % landfilling, whereas the landfilling rate in Germany was negligible. The development of waste management in Europe is illustrated in the figure below. European waste volumes are continuously increasing, it is estimated that the MSW generation will increase by 25% between 2005 and 2020 in EU-25. However, the growth rate is slowly diminishing and soon the waste volumes may also diminish. (Eurostat, 2011; (Frost & Sullivan, 2006)*




*The development of the waste management in Europe during 1995–2009 (Eurostat, 2011).*

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# Appendix 6: Detailed WEEE chain

**Waste generation**
The amount of waste electrical and electronic equipment, WEEE, is constantly growing, and is probably the fastest growing waste stream in the EU, producing 8.3–9.1 million tonnes in 2005, and the amount is expected to grow to roughly 12.3 million tonnes of WEEE by 2020. Waste electrical and electronic equipment also consists of a large amount and variety of recyclable materials, some of which are valuable, as well as a considerable variety of hazardous materials. (Törn et al., 2010.)

In Finland, the trend is similar. Data for statistics on WEEE generation has been collected systematically since 2005 when the EU WEEE-directive was put into force. Amounts of WEEE-products collected in Finland are found in Eurostat WEEE -key statistics. Both the amounts of electrical and electronic devices put onto the market as well as the amounts collected are growing steadily as is shown in Figure A. (Eurostat, 2008.)

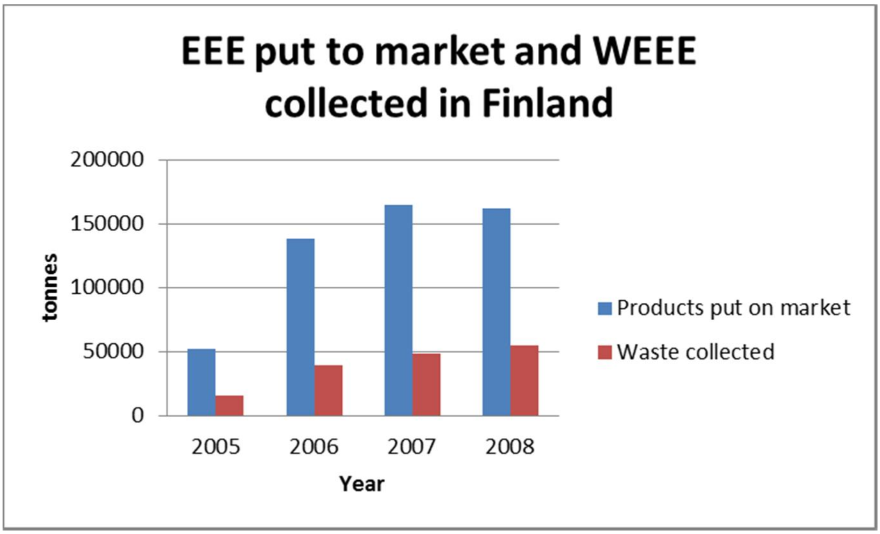


**Figure A**. EEE and WEEE in Finland development 2005–2008.

**WEEE characteristics and material composition**
Waste electrical and electronic equipment originates from households and industry. WEEE is a very versatile waste fraction and includes a vast variety of different items. They are divided into 10 categories, with several products in each category. (Directive 2002/96/EC)

***WEEE categories (Directive 2002/96/EC):***

*Category 1 – Large Household Appliances*

*This category covers appliances such as refrigerators and freezers, as well as other large appliances like washing machines, ovens, etc.*

*Category 2 – Small Household Appliances*

*This category covers all smaller household appliances such as vacuum cleaners, irons, toasters, etc.*

*Category 3 – IT and Telecommunications Equipment*

*This category covers computers (desktop and laptop) as well as e.g. printers, copiers and telephones.*

*Category 4 – Consumer Equipment*

*This category covers e.g. televisions, video recorders and DVD players, video cameras and radios*

*Category 5 – Lighting Equipment*

*Category 6 – Electrical and Electronic Tools (with the exception of large-scale stationary industrial tools)*

*This category covers: drills, saws, sewing machines, and tools for gardening or rDIY, etc.*

*Category 7 – Toys, Leisure and Sports Equipment*

*This category includes i.e. electric trains or car racing sets, hand-held video game consoles, video games, and computers for biking, diving, running, rowing, etc.,*

*Category 8 – Medical Devices (with the exception of all implanted and infected products)*

*Category 9 – Monitoring and Control Instruments, e.g.smoke detectors, heating regulators, and thermostats,*

*Category 10 – Automatic Dispensers*

These categories are defined by the type of product or the intended use of the product, and not by the type of material composition of the items or plausible similar treatment options, which would be more logical from a waste management viewpoint.

The estimated material composition of WEEE collected, according to United Nations University (2007) is shown in Figure B. The composition is very versatile. Depending on the source, and the individual samples of WEEE used in the research, there may be considerable differences in the overall composition. (Freegard & Claes, 2009; Gramatyka et al., 2007)

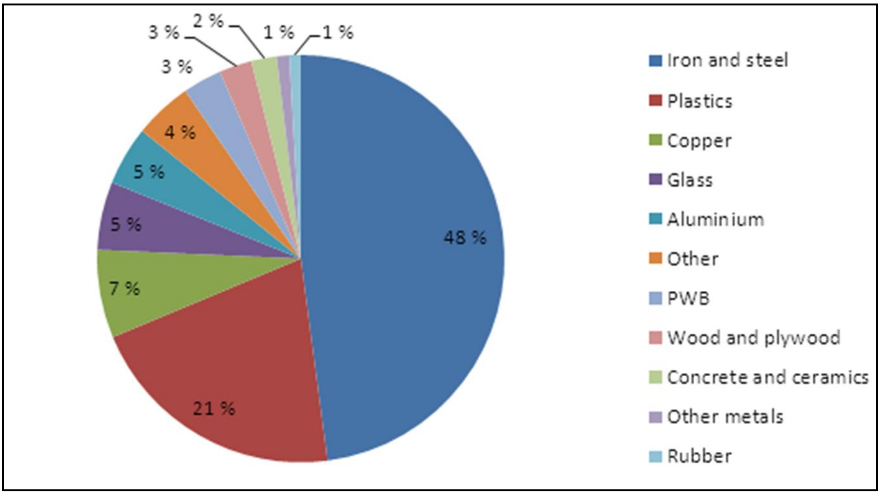


**Figure B.** Material composition of WEEE collected (United Nations University, 2007)

In this research, the focus has been on the treatment of two types of WEEE, “high value WEEE” and “low value WEEE”, according to their characteristics as waste, not according to category. High value products are found mainly in category 3 – IT and Telecommunications Equipment but also some in category 4 – Consumer Equipment can be considered to be high value or at least medium value. Typical high value products are computers, CD or DVD players and mobile phones. Although included in categories 3 and 4, computer screens and televisions are not considered to be high value WEEE. Also, products in these categories that do not have printed circuit boards or the printed circuit boards are small or do not contain valuable materials (i.e. keyboards or printers) are not high value products. Most of the value in high value products lies in the valuable metals of the printed circuit boards.

Low value products are mostly found in category 2 – Small Household Appliances, but also in category 6 – Electrical and Electronic Tools. These products consist mainly of different plastics, iron, steel, aluminium, some copper but have no or very small amounts of valuable metals. In category 7 both high and low value items can be found.

In Figures C and D the material composition of a typical high value product (personal computer) and low value product (coffee machine) can be compared. Figure 3C shows a rough distribution of the material composition of a PC. The predominant materials are ferrous metals and composite materials. “Composite materials” refers to interconnected metals and plastics, and other complex assemblies of materials. A relatively large percentage (9%) of the total mass comes from the printed circuit board of a computer.

Figure D shows a rough distribution of the material composition of a coffee machine. In the case of a coffee machine, plastic is the predominant material, but fairly large amounts of metals (non-ferrous 10% and ferrous 8%) and cable (12%) are also found. The circuit board represents only 0.3% of the mass of a coffee machine and is not even visible in the pie chart. (Chancerel & Rotter, 2009)

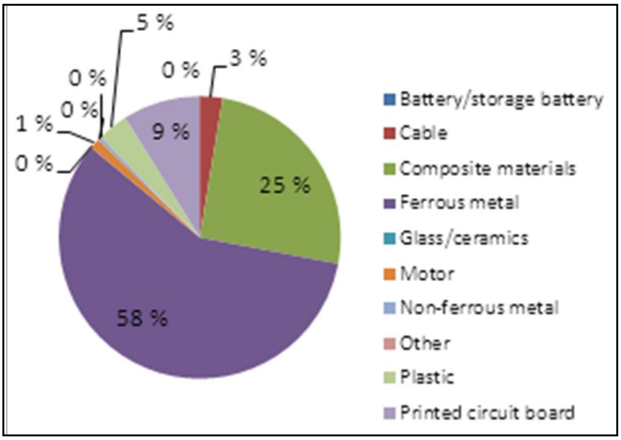


**Figure C.** Material composition of a PC.

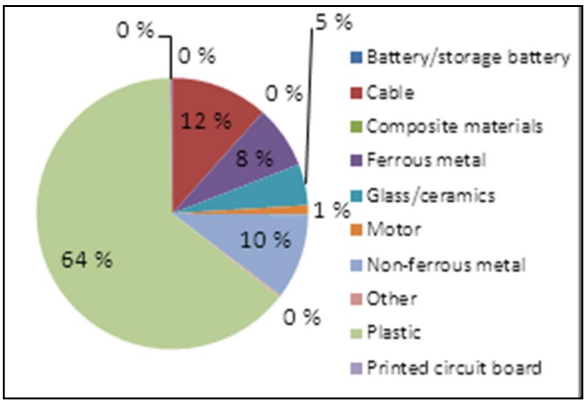


**Figure D.** Material composition of a coffee machine.

**General description of value chain**

According to EU legislation, producers are responsible for collection and recycling of these products, and collection, reuse and recycling targets have been set. (COM(2008) 810 final, Directive 2002/96/EC)

Statistics on reuse and recycling are collected separately for each EU member state. Table A shows the waste electrical and electronic equipment put on the market and collected, as well as reuse and recycling rates in Finland for 2008 in each category. Here the reuse and recycling rates are calculated on the amount recovered of the collected amounts and are therefore fairly large. The actual amounts of WEEE arising are difficult to estimate. There is still a large amount of WEEE which does not enter the collection system.

**Table A.** Statistics on WEEE recovery reuse and recycling in Finland 2008 (Eurostat, 2008).

| | Product category | Products put on the market | Waste collected | Recovery (tonnes) | Recovery rate (%) | Reuse and recycling (tonnes) | Reuse and recycling rate (%) | Reused as whole appliances (tonnes) |
|---|---|---|---|---|---|---|---|---|
| 1 | Large household appliances | 68550 | 26643 | 23614 | 89 | 22378 | 84 | 132 |
| 2 | Small household appliances | 6583 | 1745 | 1358 | 78 | 1341 | 77 | 12 |
| 3 | IT and telecommunications equipment | 31039 | 11647 | 10363 | 89 | 9816 | 84 | 129 |
| 4 | Consumer equipment | 12644 | 12293 | 9771 | 79 | 9539 | 78 | 86 |
| 5 | Lighting equipment | 12793 | 281 | 227 | 80 | 223 | 79 | 10 |
| 5a | Gas discharge lamps | 1801 | 982 | n/a | n/a | 850 | 87 | 0 |
| 6 | Electrical and electronic tools | 10656 | 401 | 307 | 76 | 304 | 76 | 2 |
| 7 | Toys, leisure and sports equipment | 3646 | 17 | 16 | 91 | 14 | 80 | 1 |
| 8 | Medical devices | 4871 | 21 | 19 | 90 | 19 | 90 | 0 |
| 9 | Monitoring and control instruments | 9191 | 53 | 45 | 84 | 40 | 75 | 1 |
| 10 | Automatic dispensers | 821 | 544 | 499 | 92 | 498 | 92 | 8 |
| | **Total amounts** | **162595** | **54627** | **46219** | **85** | **45022** | **82** | **381** |

According to the United Nations University (2007), the collection rates depending on category vary between 16.3% and 65.2%. Also, both the collected amounts and collection rates differ between different countries.

The expectation of a growing amount of WEEE in the future is based on the growth of electrical and electronic equipment put on the market (at present) in combination with the expected lifespan of each product. The lifespan of different products as well as that for the different categories varies. For computer products the average time in use is 5–6 years. This explains the fact that the amounts put on the market are much larger than the collected amounts. (Eurostat, 2008)

Even though legislation recommends reuse before recycling, only a very small amount of the WEEE is collected for reuse purposes. In reality, the amount of WEEE reused is a little larger; this is due to devices handed on to relatives or friends when purchasing new ones. These handed-down items never enter the system for collected products, and therefore do not appear in the statistics. (Ignatius et al., 2009.)

In Finland, most producers are organised into producer responsibility organisations (PROs), in order to cooperate in arranging collection and treatment. In practice, the collection is mostly arranged through municipal waste management companies, at waste stations, alongside the collection of other waste fractions and recyclables. Also some shops where EEE devices are sold accept returned devices. Some WEEE is sorted at source and some is delivered unsorted to the recycling companies.

Recycling companies process the collected products, separating materials and components for recycling. Recycled materials are utilized as raw materials in production. (Ignatius et al., 2009) The cycle of WEEE products is visualized in Figure E.

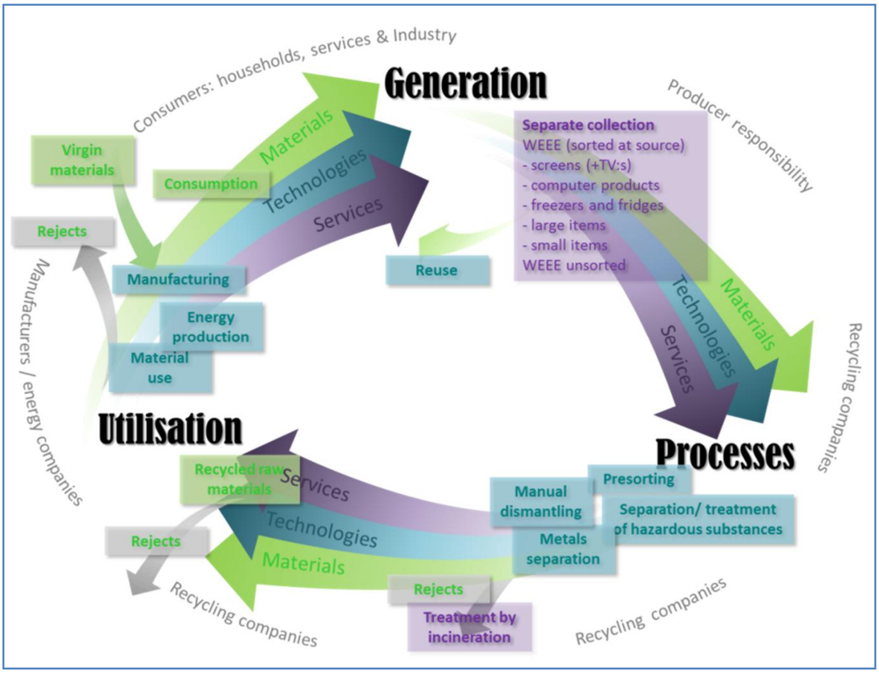


**Figure E.** The WEEE cycle.

The different materials obtained have different values, and the value also varies depending on the purity of the material obtained in the process. A desirable outcome would be to maximise the value and minimise the processing costs.

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# Appendix 7: Detailed ELV chain

This summary report is an overview of End-of-Life vehicles (ELVs): waste generation, relevant fractions and recycling technologies, system and services. The basis of the work is available data: reports and databases of the participating research institutes, the data produced by the participating industrial partners and other stakeholders as well as published literature.

**Waste generation**

In 2007 about 73 million vehicles were produced worldwide. Compared to about 38 million vehicles produced in 1980, the worldwide production of cars has grown steadily over the past decades despite a dip in 2008–2009 due the economic crisis. (Vermeulen et al., 2011) About 35 million vehicles enter the recycle infrastructure each year: in Northern America, the number of vehicles is about 13 million; in Western Europe, 11 million; in Japan, 5 million; the balance comes from the others. (Daniels, 2007) Five Member States (Germany, UK, France, Spain and) are responsible for approximately 75% of EU25 deregistration. A number of certificates of destruction (CODs), 64 851, were issued in 2011 in Finland and about 54 634 CODs in 2010 (Finnish Car Recycling, 2012a).

As a result of the stringent landfill legislation and the objectives and legislation related to ELV treatment in various countries, the treatment and disposal of ELVs has become a real challenge (Vermeulen et al., 2011). Every year, ELVs generate between 8 and 9 million tons of waste in the Community (European Commission, 2012a).

The projection in Figure A shows that the number of ELVs for the EU25 is likely to increase by 45% between 2005 and 2030. Taking into account the mass of export of used cars, which is about 2 million, it may be expected that by 2030 the total mass of ELVs generated per year in the EU25 will reach 14–17 million tonnes. (Vermeulen et al., 2011)

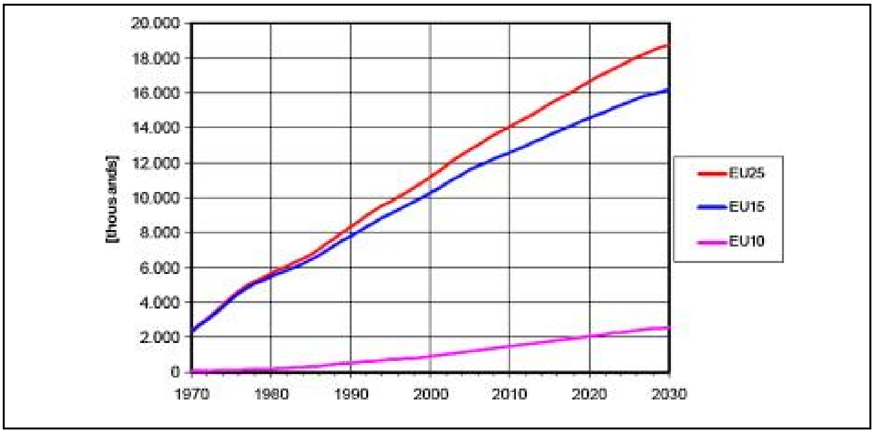


**Figure A.** Projected number of End-of-Life vehicles in the period 2005–2030 for the EU member states without Romania and Bulgaria (EU25), for the older EU countries (EU15) and for the new EU countries (EU10) (Vermeulen et al., 2011)

Different management methods are currently available, even if not all of them allow the achievement of the new European targets, defined by Directive 2000/53/EC[1]. In order to reach the Directive's targets[2], by 2015, 95% of an ELV should be recovered; including 10% waste to energy, of which 85% is recycled or reused respectively. According to Sakkas and Manios (2003): "The core problem behind the disputes with regard to the Directive is the high cost of the extra recycling required to reach the targets it sets".

**Relevant fractions**

Ferrous metals, which are mainly composed of iron and have magnetic properties, are the main component of an ELV (Bureau of International Recycling, 2012a). ELVs also contain non-ferrous metals, such as aluminium, copper, lead, zinc, and nickel (Bureau of International Recycling, 2012b). Figure B shows that currently about 75% of an ELV's total weight is recyclable. The remaining 25% is called Automotive Shredder Residue (ASR or SR) or car fluff. In Europe ASR is classified as hazardous waste due to its heterogeneous composition and heavy metal content. (Vermeulen et al., 2011) ASR is made of plastic (19–31%), rubber (20%),

[1] "Parliament adopted the Amendment of the Waste Act (452/2004) on June 4, 2004, by which producer liability regulations were introduced into Finnish legislation. The government for its part adopted the End-of-Life Vehicle Degree (581/2004) on June 23, 2004. The EU Directive on End-of-life Vehicles (2000/53/EC) was implemented through these regulations. The legislation came into force on September 1, 2004. It covers passenger cars, vans and special-purpose vehicles such as recreational vehicles." (Finnish Car Recycling, 2012b)

[2] "The recycling and recovery rate of End-of-Life Vehicles is the most relevant data because of the reporting requirements and targets set out in the End-of-Life Vehicles Directive" (European Commission, 2011).

textiles and fibre materials (10–42%) and wood (2–5%), which are contaminated with metals (8%), oils (5%), and other substances, some of which may be hazardous (about 10%), e.g. PCB, cadmium and lead. (Nourreddine, 2007) The standard method of ASR disposal has been landfilling, now limited by the stringent legislation and the objectives/legislation related to ELV treatment of various countries. (Vermeulen et al., 2011)

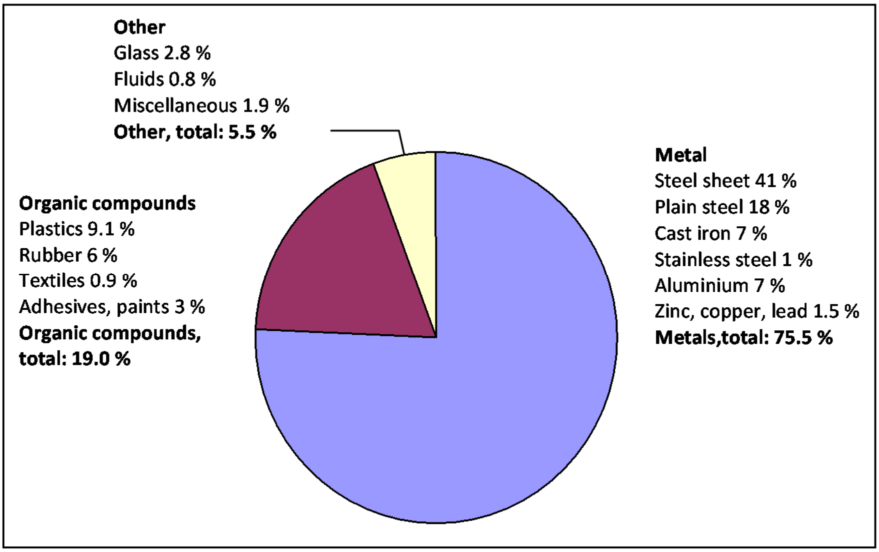


**Figure B.** Average material content of ELV (data source: Finnish Car Recycling, 2012c).

**Recycling technologies, system and services**

On a new vehicle, for which component parts, material or both can be taken into account, the calculation of the recyclability and recoverability rates are carried out using four main steps illustrated in Figure C: Depollution, dismantling, metals separation and non-metallic residue treatment (ISO 22628:2002).

Depollution concerns about 3% in weight of ELV materials.It involves the removal batteries, fluids, heavy metals containing components, or potentially explosive elements (e.g. airbags). (Morselli et al., 2010.)

Dismantling consists of the removal of valuable parts and materials which can be re-used or recycled (e.g. glass, metallic components containing aluminium, magnesium, copper, rubber and plastic elements). The weight percentage of the parts removed depends on the dismantling plant: values range from 9% for old (natural) ELVs to 47% for new (premature, e.g. damaged) ones (Morselli et al., 2010). Certain other of the vehicles' reusable or recyclable component parts may be taken into account. Based on the general requirement, component parts shall be considered as reusable, recyclable or both (dismantling based on its accessibility, fastening technology and proven dismantling technologies). As a specific requirement, a component part shall be considered as recyclable, based on its material composition, and proven recycling technologies. In order to be recyclable, a component part or material shall be linked to a proven recycling technology. An additional requirement is that the reusability of a component part shall be subject to the consideration of safety and environmental hazards. (ISO 22628:2002.) Materials from de-pollution and dismantling (in tonnes per year) of ELV arising in Finland is shown Figure D.

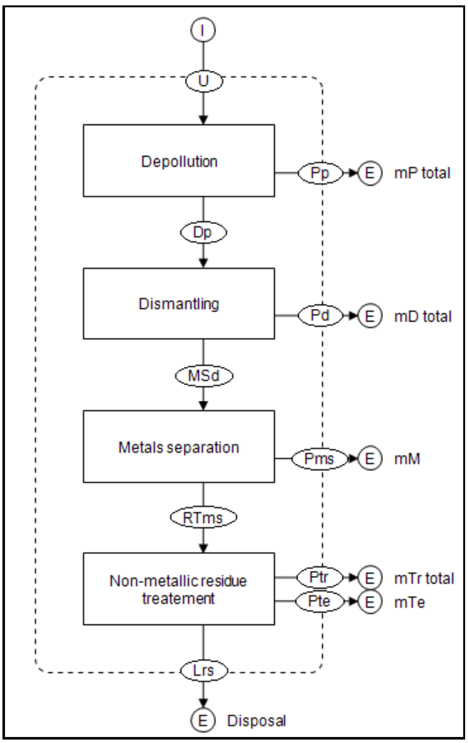


**Figure C.** ELV depollution and dismantling scheme. (Morselli et al., 2010.)

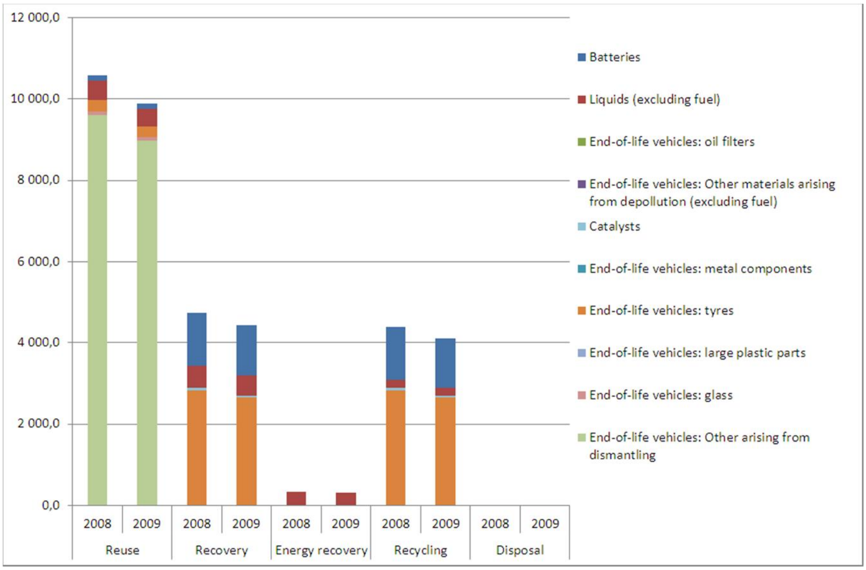


**Figure D.** Materials from de-pollution and dismantling (in tonnes per year) of End-of-Life vehicles in Finland 2008–2009 (data source: European Commission, 2012c).

All metals, ferrous and non-ferrous, which have not already been accounted for in the previous processes will be taken into account in Metals separation. Both ferrous and non-ferrous metals are considered recyclable: 72% for ferrous products and 1–3% separated non-ferrous product (ISO 22628:2002) (Forton et. al., 2006; Redin et al., 2010). Materials from shredding (in tonnes per year) of ELVs arising in Finland are shown in Figure E.

The other materials remaining constitute the non-metallic residue. At this step, the residual non-metallic recyclable materials or both these materials and the residual non-metallic recoverable materials may be taken into account. Light fraction fluff, size > 30 mm, represents about 50% of the total ASR or SR stream (approximately 25% of an ELV). Considering only the coarse and oversize fraction, typically 40% can potentially be recovered (i.e. 20% of total ASR or 5% of an ELV) (Forton et al., 2006; Redin et. al., 2010).

Under evaluation by both car producer and recycling companies at this time, great innovations are expected in the next years, i.e. concerning material separation enhancement, thermo-chemical conversion (gasification and pyrolysis) and recycling/recovery routes of the residue. (Vermeulen et al., 2011) Possible upgrading by secondary recovery techniques can produce a fuel grade or filler grade ASR (the application in waste-to-energy plants, in cement kilns or in metallurgical processes is possible with limitations). The ASR quantities are likely to increase in the coming years due to the growing number of cars being scrapped and the increase in the amount of plastics used in car production. (Morselli et al., 2010)

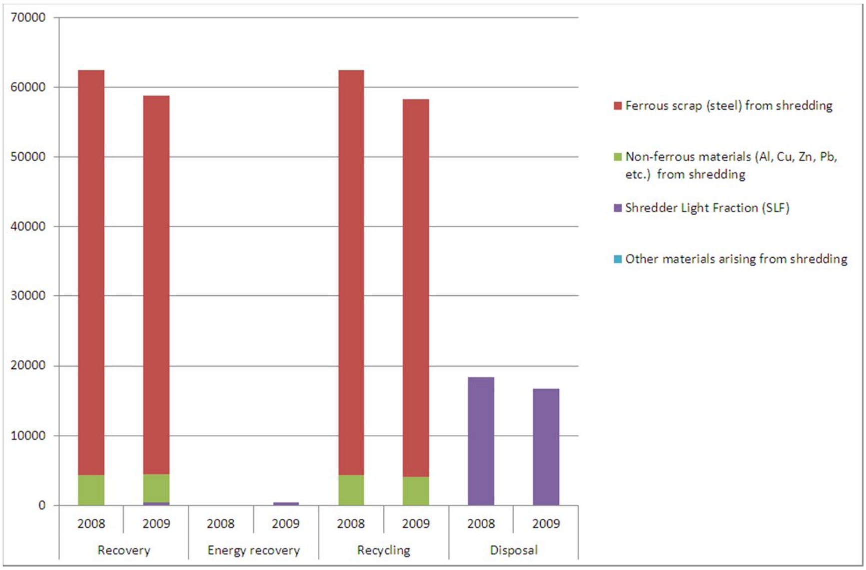


**Figure E.** Materials from shredding (in tonnes per year) of end-of-life vehicle in Finland 2008–2009 (data source: European Commission, 2012d).

**General description of the value chain**

The ELV value chain (Figure F) consists of three main steps: generation (including collection, transport and storage), processing and utilisation of the recycled materials. The further processing generally includes mechanical and/or chemical processing and further refining or utilization as a material or as a fuel in energy production. In all the steps some rejects are generated. The value chain of End-of-Life vehicle management (ELVM) comprises a number of business entities involving one or more aspects of ELVM management processing. (Sakkas & Manios, 2003.)

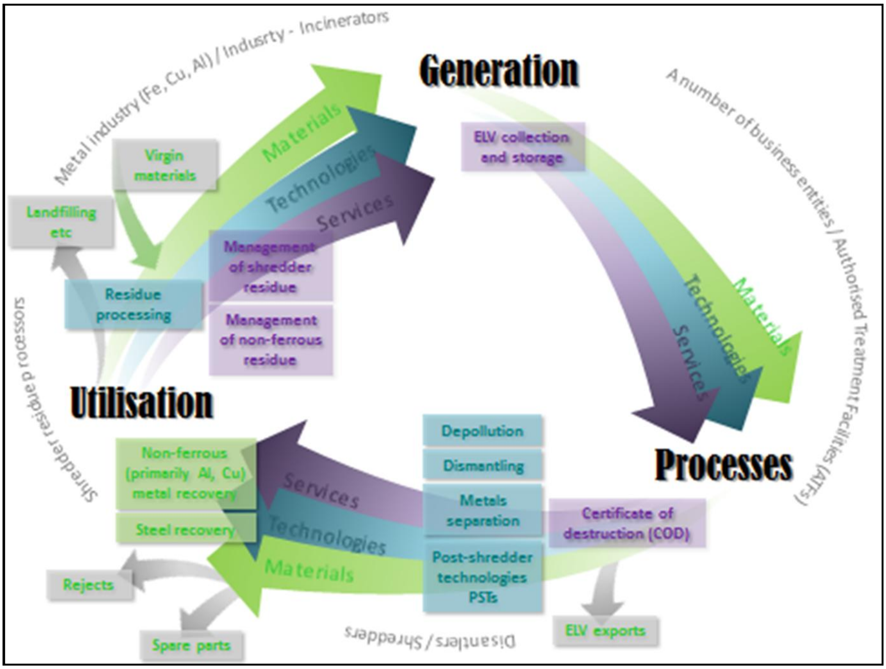


**Figure F.** The End-of-Life vehicle value chain containing generation, processing and utilisation.

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Series title and number
**VTT Technology 60**

| Title | **Directions of future developments in waste recycling** |
|---|---|
| Author(s) | Malin Meinander & Ulla-Maija Mroueh (Eds.), John Bacher, Jutta Laine-Ylijoki, Margareta Wahlström, Johannes Jermakka, Nina Teirasvuo, Hannele Kuosa, Maria Törn, Johanna Laaksonen, Jukka Heiskanen, Juha Kaila, Hanna Vanhanen, Helena Dahlbo, Kaarina Saramäki, Timo Jouttijärvi, Tuomas Mattila, Risto Retkin, Pirke Suoheimo, Katja Lähtinen, Susanna Sironen, Jaana Sorvari, Tuuli Myllymaa, Jouni Havukainen, Mika Horttanainen, and Mika Luoranen |
| Abstract | This publication summarises the results and conclusions of the research project Advanced Solutions for Recycling of Complex and New Materials. The aim of the project has been to create a understanding of the future development needs of waste recycling and management by carrying out an in-depth analysis of five selected waste value chains. The chains analysed were:<br>• Construction and demolition (C&D) waste<br>• Commercial and industrial waste (C&I)<br>• Household waste / municipal solid waste (MSW)<br>• Waste electrical and electronic equipment (WEEE)<br>• End-of-Life vehicles (ELV).<br>The main emphasis is on the analysis of the five waste chains; including technologies, material utilisation and losses, as well as environmental and economic analyses of the current systems. The current and future requirements of the Finnish operational and business environment are also studied. The findings of the project are to be applicable in the planning and implementation of future development projects, as well as in decision making by various actors in the sector.<br>The main methodologies used in this study were literature reviews, data collection, interviews and waste chain modelling; material flow analysis (MFA), life cycle assessment (LCA) focusing on climate impacts and resource use and life cycle cost analysis (LCC). Value formation was studied in WEEE and ELV chains.<br>The operational environment in the waste management chains is affected by various environmental and other policies and regulations, demand and supply as well as raw material prices. Cultural aspects and people's attitudes are also important, especially because the waste market will be increasingly global.<br>The stricter recycling targets are expected to affect product eco-design and development of innovations in the field. Increased recycling calls for systemic thinking and improved waste chain management with more efficient processes and technologies. Integrated modelling concepts and analysis of future scenarios are needed for an analysis of the economic viability of the recycling solutions. Development of new presorting and pretreatment concepts could, for example, improve both the quality and quantity of products. Management of the whole treatment chain calls for real-time monitoring methods integrated with on-line quality control. |
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| Pages | 86 p. + app. 80 p. |
| Name of the project | NeReMa Advanced Solutions for Recycling of Complex and New Materials |
| Keywords | Waste chain management, material flow analysis, LCA, commercial and industrial waste, municipal waste, construction and demolition waste, waste electrical and electronic equipment, end-of-life vehicles, future development |
| Publisher | VTT Technical Research Centre of Finland<br>P.O. Box 1000, FI-02044 VTT, Finland, Tel. 020 722 111 |

Julkaisun sarja ja numero
**VTT Technology 60**

| | |
|---|---|
| Nimeke | **Kestävän kierrätyksen tulevaisuuden kehityssuuntia** |
| Tekijä(t) | Malin Meinander & Ulla-Maija Mroueh (Eds.), John Bacher, Jutta Laine-Ylijoki, Margareta Wahlström, Johannes Jermakka, Nina Teirasvuo, Maria Törn, Johanna Laaksonen, Jukka Heiskanen, Juha Kaila, Hanna Vanhanen, Helena Dahlbo, Kaarina Saramäki, Timo Jouttijärvi, Tuomas Mattila, Risto Retkin, Pirke Suoheimo, Katja Lähtinen, Susanna Sironen, Jaana Sorvari, Tuuli Myllymaa, Jouni Havukainen, Mika Horttanainen, and Mika Luoranen |
| Tiivistelmä | Tässä julkaisussa esitetään tutkimusprojektin ”Advanced Solutions for Recycling of Complex and New Materials” tuloksia ja johtopäätöksiä. Hankkeen tavoitteena oli luoda käsitys jätehuollon tulevaisuuden kehitystarpeista syventymällä viiteen jäteketjuun:<br>• Rakennus- ja purkujäte (C&D)<br>• Kaupan ja teollisuuden jätteet (C&I)<br>• Kotitalousjäte / yhdyskuntajäte (MSW)<br>• Sähkö- ja elektroniikkaromu, SER (WEEE)<br>• Romuautot (ELV).<br>Tutkimuksessa analysoitiin Suomen jäte- ja kierrätysalan toimintaketjuja ja -ympäristöä tavoitteena luoda ymmärrystä tulevaisuuden kehittämistarpeista. Työssä keskityttiin valittujen arvoketjujen nykytilan analyysiin erityisesti seuraavista näkökulmista: teknologiat, materiaalien hyödyntämisasteet ja materiaalihäviöt sekä merkittävimpien ympäristövaikutusten ja taloudellisten vaikutusten analyysit. Tuloksia voidaan hyödyntää tulevaisuuden suunnittelu- ja kehitysprojekteissa. Ne tukevat myös jäte- ja kierrätysalan päätöksentekoa.<br>Tutkimusmenetelminä käytettiin kirjallisuusselvityksiä, tiedonkeruuta, haastatteluja sekä arvoketjujen mallinnusmenetelmiä: materiaalivirta-analyysit, elinkaarianalyysit keskittyen erityisesti ilmastovaikutuksiin ja luonnonvarojen käyttöön sekä elinkaarikustannusten arviointi esimerkkitapauksessa. Lisäksi tarkasteltiin arvonmuodostusta SER- ja WEEE-ketjuissa.<br>Kierrätys- ja jätehuoltoalan toimintaympäristöön vaikuttavat erityisesti lainsäädäntö, kysynnän ja tarjonnan kehittyminen sekä materiaalien ja energian hinnat. Myös kulttuurinen ja asenneympäristö on tärkeä, varsinkin kun alan markkinat ovat yhä enemmän maailmanlaajuisia. Kuten muillakin aloilla sidosryhmien merkitys on kasvamassa.<br>Raaka-aineiden hintojen nousun ja tiukkenevien kierrätystavoitteiden voidaan tulevaisuudessa odottaa johtavan uusien innovaatioiden syntymiseen ja käyttöönottoon sekä vähitellen kierrätystä tukevien tuotesuunnittelumenetelmien kehitykseen. Kierrätyksen tehostaminen edellyttää systeemistä ajattelua, jätevirtojen hallinnan menetelmien kehittämistä sekä tehokkaampia erottelu- ja lajitteluteknologioita koko keräys- ja käsittelyketjuun. Taloudellisten edellytysten arviointiin tarvitaan eri näkökulmia yhdistäviä mallinnuskonsepteja ja tulevaisuuden skenaarioiden tarkastelua. Tuotteiden saantoa ja laatua voidaan parantaa mm. kehittämällä esilajittelun ja –erottelun tehostamiseen uusia konsepteja. Koko käsittelyketjun ja tuotteen laadun hallitsemiseksi tarvitaan eri virtojen reaaliaikaista monitorointia yhdistettynä on-line laadunvalvontamenetelmiin. |
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| Sivumäärä | 86 s. + liitt. 80 s. |
| Projektin nimi | NeReMa Advanced Solutions for Recycling of Complex and New Materials |
| Avainsanat | Waste chain management, material flow analysis, LCA, commercial and industrial waste, municipal waste, construction and demolition waste, waste electrical and electronic equipment, end-of-life vehicles, future development |
| Julkaisija | VTT<br>PL 1000, 02044 VTT, Puh. 020 722 111 |

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