

Non-CO₂ Greenhouse Gases

Emissions Abatement of Fluorinated Greenhouse Gases

Fluorattujen kasvihuonekaasujen päästöjen vähentäminen

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Abstract

This paper concerns technical options and costs of reduction emissions of HFCs, PFCs and sulphur hexafluoride (SF₆) in Finland. Currently, Finnish emissions of these gases are marginal but are projected to grow five-fold during the next two decades. Most of the forecasted increase is due to substitution of ozone depleting refrigerants by HFCs in refrigeration and air conditioning systems. Cooling systems are also predicted to become more common. This paper is especially focused on dealing with technical measures to reduce refrigerant emissions by using alternative gases and technologies or leakage reduction (containment). Larger abatement in emissions could be achieved using alternative refrigerants and technologies, but their applicability and cost effectiveness is lower compared to containment measures. Economic impacts on different types of companies due to implementation of reduction options may differ significantly depending mainly on the line of business.

Lyhennelmä

Fluoratuista kasvihuonekaasuista HFC- ja PFC-yhdisteet sekä rikkiheksafluoridi kuuluvat Kioton pöytäkirjassa säänneltäviin kasvihuonekaasuihin. Näiden voimakkaiden kasvihuonekaasujen päästöt ovat toistaiseksi olleet varsin vähäisiä Suomes-

sa, mutta päästöjen ennakoitaan viisinkertaistuvan seuraavan kahdenkymmenen vuoden aikana. Tämä johtuu pääasiassa yläilmakehän otsonia tuhoavien kylmäaineiden korvaamisesta HFC-yhdisteillä sekä kylmä- ja ilmastointilaitesovellusten arvioidusta yleistymisestä. Tällöin näiden päästöjen merkitys kokonaisuuden kannalta olisi paljon nykyistä suurempi. Tässä artikkelissa keskitytään tarkastelemaan HFC- ja PFC-yhdisteiden sekä rikkiheksafluoridin perusuran mukaisten päästöjen kehitystä Suomessa sekä erityisesti päästöjen teknisistä vähentämismahdollisuuksista kylmä- ja ilmastointilaitteista. Tarkastellut päästövähennystoimet on jaettu kahteen ryhmään: vaihtoehtoisten kylmäaineiden tai teknisten ratkaisujen käyttöönottoon sekä vuotojen vähentämiseen tähtääviin toimiin, joita on arvioitu myös rikkiheksafluoridieristeisten sähkönjakelulaitteiden osalta. Vaihtoehtoisten kylmäaineiden käyttöön saattaa liittyä turvallisuusongelmia kylmäaineen syttyvyyden tai myrkyllisyyden vuoksi. Näiden ongelmien ehkäiseminen puolestaan aiheuttaa kustannuksia ja saattaa lisätä järjestelmien energiankulutusta. Vuotojen vähentäminen osoittautui pääsääntöisesti selvästi kustannustehokkaammaksi menetelmäksi rajoittaa päästöjä kuin vaihtoehtoisten teknisten ratkaisujen käyttöönotto, mutta saavutettu päästövähennys jäi jonkin verran pienemmäksi. Päästövähennystoimien käyttöönotosta aiheutuvat taloudelliset vaikutukset erityyppisiin yrityksiin saattavat olla hyvin erilaisia.

1 Introduction

Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆) are relatively new synthetic compounds which are used in different types of industrial purposes. These com-

pounds act as effective greenhouse gases and they have typically long lifetimes in the atmosphere, but they are not harmful to stratospheric ozone.

Emissions of carbon dioxide, methane, nitrous oxide, HFCs, PFCs and sulphur hexafluoride are regulated by the Kyoto Protocol under the United Nations Framework Convention on Climate Change (UNFCCC). Currently, the contribution of HFCs, PFCs and SF₆ to greenhouse gas emissions is marginal, representing some two percentages worldwide and only half a percent in Finland. However, emissions of these fluorinated gases are expected to grow rapidly, mainly due to increasing use of HFCs to substitute ozone depleting substances, such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and halons.

Largest amounts of HFCs are used as refrigerants, but also as foam blowing agents, aerosol propellants and extinguishants in fixed fire fighting systems. PFCs are to some extent also used as replacements to ozone depleting refrigerants. Worldwide, however, most of the PFC consumption is due to use as process gases in semiconductor manufacturing. In Finland this use is minor. The most common applications of SF₆ are to provide electrical insulation in high voltage electrical equipment and to act as protective gas in magnesium die casting.

In 1990 the Finnish emissions of HFCs, PFCs and SF₆ amounted to some 0.05 million metric tons of carbon dioxide equivalent (Mt CO₂ eq.), representing some 0.1% of total emissions of all Kyoto greenhouse gases (fig. 1). The low level of emissions in early 1990s was due to lack of some major emission sources of HFCs and PFCs, such as primary aluminium industry, HCFC-22 manufacturing and production of HFCs, PFCs and SF₆, in Finland.

The situation began to change rapidly around 1994–1995, in concomitance with the phasing-out and replacement of ozone depleting substances in refrigeration and air conditioning applications as well as in some aerosol, foam blowing and fire fighting applications. Since the phasing-out of ozone depleting substances is still an on-going process, the observed growth in emissions of HFCs is expected to continue.

Currently, some 75% of total Finnish emissions of HFCs, PFCs and SF₆ are due to HFC emissions from refrigeration and air conditioning. This contribution is expected to increase to some 90% by the first Kyoto commitment period and onwards if no additional emission abatement measures were carried out (fig. 1). The most part of the projected emission reduction potential is thus directly connected with refrigerant emissions.

This paper explains how projections were carried out, and presents the results of an analysis in which two major types of abatement options (using alternative gases and technologies, leakage reduction) were compared in terms of their emission reduction potential and costs. The time period considered extends to 2020. Given the large projected share of refrigerant emissions in the future, the paper will focus on measures to limit these emissions from refrigeration and air conditioning systems. Changes in economic competitiveness of companies resulting from the introduction of these abatement options will also be considered at a general level.

For some of the emission sources present in Finland, quantitative emission reduction scenarios could not be formulated. This was either due to lack of information regarding the basic parameters required in modelling, or because viable reduction measures were not identified. These emission sources are accounted in scenarios with no additional emission reduction measures. Qualitative treatment of emission abatement options of these sources can be found in the final report of this project (Oinonen and Soimakallio 2001), and will not be considered in this paper.

2 Modelling of emissions and costs

2.1 Baseline scenarios

An overall baseline scenario was constructed from 20 emission sources covering all sources of HFC, PFC and SF₆ emissions, for which sufficient amount of data was available to produce quantitative emission estimates. Emission scenarios were not calculated at all for certain minor sources (e.g. use of SF₆ in soundproofing double glazing), because sufficient amount of data was not available.

The refrigeration and air conditioning sector was divided to suitable categories, and baseline scenarios were calculated for each one by one. These individual categories included domestic and other small stand-alone equipment, commercial refrigerating systems, industrial refrigeration (food processing and cold storage as well as other process cooling), ice rinks, professional kitchens, transport refrigeration, stationary and mobile air conditioning as well as residential and other heat pumps.

Baseline scenarios were also calculated for some manufacturing processes, products and equipment. These include one component and other polyurethane foam, technical aerosols and metered dose inhalers, fixed fire fighting systems, semiconductor manufacturing, magnesium die casting and electrical equipment.

Emissions were modelled as directly proportional to activity level and emission factor. Emissions were calculated for manufacturing/installation, use and disposal phases of life, if present in Finland. Data on activity levels (for instance, numbers of installed equipment, average charges) were obtained through a number of company surveys carried out by the Finnish Environment Institute in 1999 and 2000. Emission factors were based on expert judgement, typically the mid-point value of ranges given in IPCC's Good Practice Guidance (IPCC 2000) were used. Technological and regulatory changes as well as changes in activity data were modelled into the baseline scenario, if considered necessary. For instance, we assumed that legislation would be extended from CFCs and HCFCs to include mandatory gas recovery of HFC and PFC refrigerants. The basic parameters and assumptions behind all individual baseline scenarios were reviewed by Finnish experts of relevant fields.

2.2 Reduction scenarios and costs

Scenarios including additional emission abatement options compared to a baseline were calculated for all individual refrigeration and air conditioning sources described in the previous section (excluding commercial stand-alone equipment and heat pumps) as well as for electrical equipment. For refrigeration and air conditioning

sources, two major types of emission reduction options were considered in the analysis, if applicable: leakage reduction (containment), and total or partial substitution of fluorinated gases by using alternative substances and technologies. For electrical equipment, only enhanced recovery practices were examined, because the substitution of SF₆ is not in most cases a viable option.

Measures based on alternative gases and technologies were applied to new systems only due to difficult application to existing refrigeration and air conditioning systems. Instead, leakage reduction options as well as extended recovery practices for electrical equipment were applied to both existing stock and new systems. Measures were timed to begin in 2002, if applicable given their technological maturity.

Preliminary assessment of abatement options and costs were based on a literature review. These assessments were then developed into reduction scenarios and subjected to a review by relevant Finnish experts. Emission factors, cost and other estimates were adjusted if experts provided differing, well reasoned and solidly argued information (Oinonen and Soimakallio 2001).

Possible increase in energy (electricity) consumption and emissions from electricity production due to adoption of substitutive refrigerant or cooling technology were modelled into relevant reduction scenarios. Emissions from Finnish electricity production were calculated using an average factor of 250 g CO₂/kWh_e (Lehtilä et al. 1997). Costs from increased energy consumption were calculated based on 0.067 €/kWh_e average electricity price for small-scale industry (MTI 2000). A discount rate of 4% was used.

3 Technical and economic evaluation of emission reduction options

3.1 Baseline emissions

The overall baseline emissions were projected to reach a level of 1.7 Mt CO₂ eq. during the first Kyoto commitment period and some 2.2 Mt CO₂

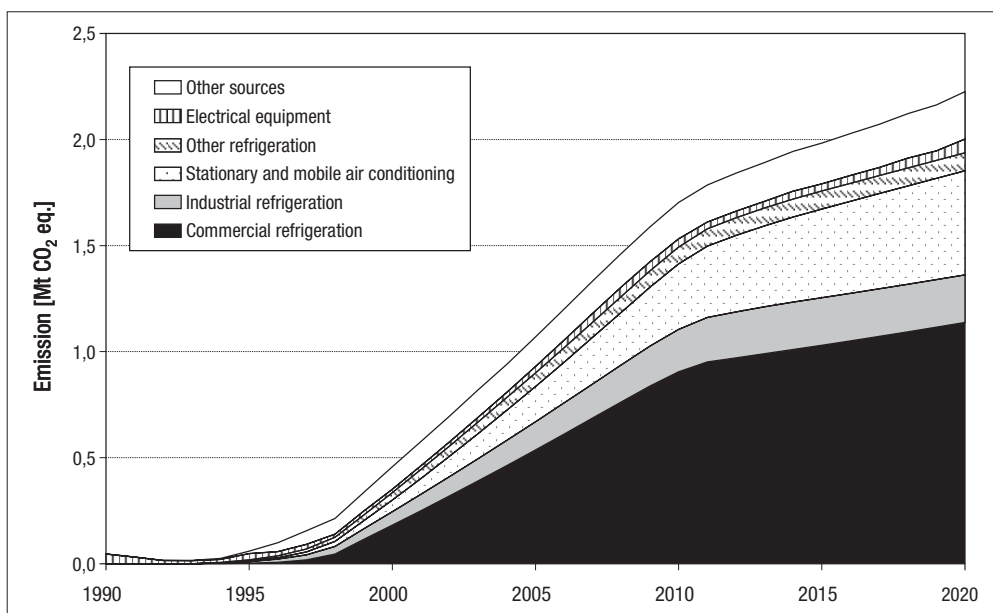


Figure 1. Emissions according to the baseline scenario (Oinonen and Soimakallio 2001).

eq. in 2020, respectively (fig. 1). Approximately half of these emissions were projected to take place due to leakage from commercial refrigeration, whereas industrial refrigeration accounts for some 20%. The contribution of mobile and stationary air conditioning was estimated to be some 10% each. Share of electrical equipment in total emissions of HFCs, PFCs and SF₆ is estimated to be minor (fig. 1). Total emissions of the other sources, including foam blowing agents, aerosol propellants, magnesium die-casting, semiconductor manufacturing and fixed fire fighting systems, is expected to double by 2020 compared to the current level (fig. 1). However, the overall contribution of these emissions is at the same time decreasing from 25% to 10%, as mentioned in the first section.

The cost-effectiveness of an emission abatement option depends directly on costs and achieved emission reduction following the implementation of the measure. In order to apply relevant option, phases of life of sources that give rise to highest share of emissions had to be recognised.

Typically, emissions taking place during manufacturing or installation of refrigeration and air condi-

tioning systems are at a level of less than one to five percent of refrigerant charge. Instead, there are many differences between different types of systems regarding leakages during operation. The emissions vary depending mainly on the type of system, conditions of use and quality of components as well as practices used to carry out maintenance. Domestic and other small stand-alone refrigerators equipped with hermetic compressors are relatively leak tight, and thus emissions during operation are minor. Instead, medium sized and large commercial and industrial refrigeration and air conditioning systems may leak 10 to 30% of their refrigerant charge per annum. Mobile air conditioning and transport refrigeration systems are particularly prompt to leakage due to vibration and variable climatic conditions, for instance.

SF₆ leakage from electrical equipment during normal operation is usually at a low level, because the gas is enclosed tightly in the equipment. Furthermore, gas recovery practices have improved resulting in a decrease in manufacture as well as maintenance emissions in relation to gas consumption. However, we projected that there are still opportunities to improve gas recovery.

3.2 Alternative substances and technologies

Main reasons to use fluorinated refrigerants are connected to their relatively advantageous thermodynamic properties to provide cooling energy efficiently, cost effectively and safely. Most of HFC and PFC refrigerants as well as their ozone depleting precursors are non-toxic and incombustible. Therefore, the evaporator of a refrigeration or air conditioning system can be installed directly in the place to be cooled without safety risks, to provide cooling energy efficiently. Technology of this kind is called *direct cooling* and it is globally dominant in refrigeration applications.

Most potential substitutes for fluorinated refrigerants are ammonia, hydrocarbons and carbon dioxide. The main difficulties with these refrigerants are that ammonia is toxic, hydrocarbons are flammable and the thermodynamic properties of carbon dioxide are complicated.

If ammonia or hydrocarbons are used in applications placed in public areas, appropriate precautions are required. Hydrocarbons can be used safely in applications based on direct cooling equipped with a hermetic compressor and relatively small charge of refrigerant. Examples are domestic refrigerators and small residential heat pumps. Larger refrigeration systems using hydrocarbons or ammonia have to be equipped with secondary loop systems to provide *indirect cooling*, in which cooling energy is brought to target by means of a heat transfer fluid. Even if secondary loop systems are used, there can be applications where the use of alternative refrigerants is not a viable option due to safety or other reasons. In that case, the use of indirect cooling and condensation with HFC as a refrigerant enable minimisation of required HFC-charge.

Using secondary loops instead of direct cooling may be associated with some disadvantages. Total energy efficiency is lower resulting typically in 10–20% higher energy consumption when using secondary loops compared to similar system using direct cooling. Besides, investments will usually increase by 10–30%, and maintenance costs are some 20% higher compared to direct cooling sys-

tems. However, achievable reductions in total emissions are significant.

Abatement options based on alternative substances and technologies were analysed for six individual refrigeration or air conditioning sources (table 1). Indirect refrigeration using hydrocarbons or ammonia was assumed to be suitable for process cooling, stationary air conditioning and half of the food processing refrigeration. It has to be noted that virtually all currently installed process cooling systems as well as part of stationary air conditioning systems are based on indirect cooling already, resulting in lower investments and other costs for substituting the refrigerant. However, we estimated that only 30% of process cooling systems could use ammonia or hydrocarbons due to safety and other reasons. Indirect HFC-systems were assumed to substitute direct HFC-refrigeration in commercial and in half of the food processing system installations. We also calculated achievable emission reductions for substituting HFC-refrigerant by isobutane in domestic refrigeration. Carbon dioxide was assumed to be mature and introduced to mobile air conditioning systems in 2004, with no energy penalty.

Cost effectiveness of evaluated options based on alternative gases and technologies varied between some 10 and 60 euros per abated ton of carbon dioxide equivalent (table 1). Very high abatement costs were calculated for domestic refrigeration, resulting from the virtually non-existing emission reduction potential for this type of equipment.

3.3 Containment

Emissions of HFCs from refrigeration and air conditioning systems, as well as SF₆ from electrical equipment, can be mitigated by paying attention to factors that may cause the gas to escape from the system. Different leakage reduction measures range from improved system design and selection of components to use of leak detectors and improved service practices. Containment measures should also be extended to the decommissioning phase by recovering the gas, in order to maintain the benefit achieved during other phases of equipment life.

Based on literature and expert review, we estimated that, by implementing improved maintenance practices, 40% of refrigerant emissions could be reduced during the use and disposal of fixed refrigeration and air conditioning systems. Sufficient improvement in service practices to reach this target is projected to increase maintenance costs by 50%. In addition, by investing a few percent more for tightness of refrigerating systems, a total reduction of 60% can be achieved. Despite the fact that gas recovery at disposal was included in the baseline, we estimated that further 20% of disposal emissions could be reduced by the implementation of improved practices.

Leakage reduction options of the same kind were also evaluated for transport refrigeration and mobile air conditioning systems, with relevant estimates of costs as well as achievable reductions in emissions. Additional containment measures compared to the baseline were not considered necessary for domestic and other small stand-alone refrigerators, nor for heat pumps, due to the tightness of these systems.

We assumed that by extending gas recovery and recycling SF₆ emissions due to maintenance of electrical equipment could be reduced by 25%.

Cost effectiveness of individual containment options was typically some 15 euros per abated ton of carbon dioxide equivalent, but varied between a few and some 40 €/t CO₂ eq. (table 1). Apart from process cooling and stationary air conditioning systems, individual leakage reduction options would appear to be clearly more cost effective compared to measures based on alternatives.

3.4 Overall reduction scenarios and costs

Individual emission reduction scenarios were grouped to two sets of scenarios. Reduction scenario 1 contains measures with the highest long-term net reductions in greenhouse gas emissions. Alternative gases and technologies were chosen if applicable, except in case of process cooling (see chapter 1.2). Reduction scenario 2 was based on containment measures only. Baseline emissions were halved in both reduction scenarios during the

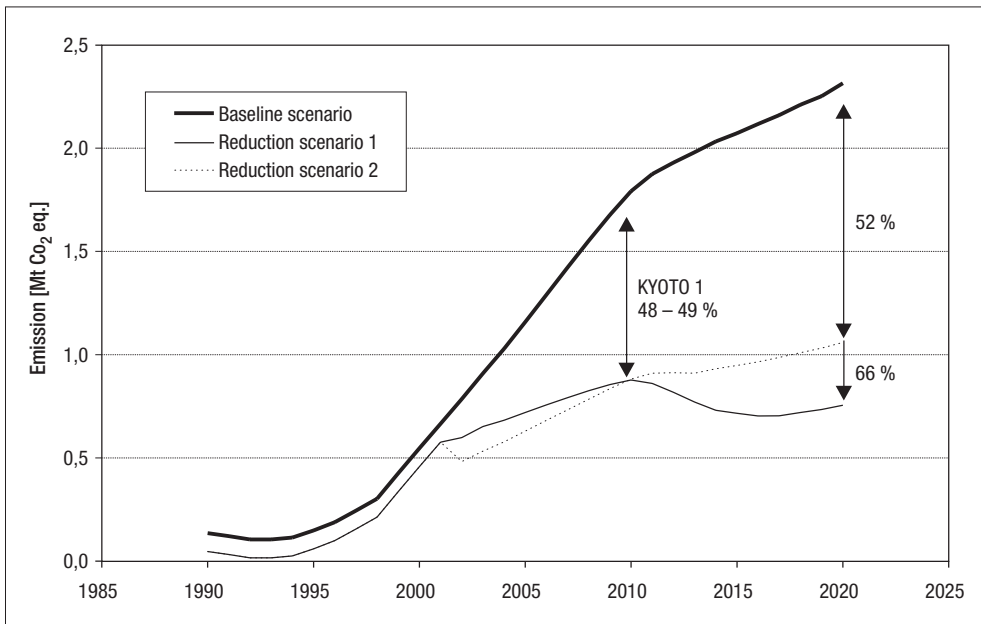


Figure 2. Overall baseline scenario compared with reduction scenarios 1 and 2.

Table 1. Cost effectiveness, total cost and emission reductions calculated for various sources and abatement options.

| Emission sources and abatement options | Cost effectiveness [€/t CO ₂ eq.] | | Total cumulative cost [M€] | | Emission reduction [kt CO ₂ eq./a] | |
|--|---|------------------|-------------------------------|------|--|-------|
| | KYOTO 1 | 2020 | 2012 | 2020 | KYOTO 1 | 2020 |
| Domestic refrigeration (isobutane) | 3 678 | 948 | 50 | 76 | ~ 0 | < 10 |
| Commercial refrigeration (indirect HFC-system) | 43 | 29 | 181 | 350 | 470 | 770 |
| Commercial refrigeration (leakage reduction) | 12 | 8 | 51 | 89 | 480 | 650 |
| Food processing and cold storage (NH ₃ /HCs/HFCs) | 59 | 38 | 27 | 55 | 50 | 90 |
| Food processing and cold storage (leakage reduction) | 14 | 9 | 7 | 12 | 50 | 70 |
| Process cooling (NH ₃ /HCs) | 16 | 11 | 3 | 5 | 20 | 30 |
| Process cooling (leakage reduction) | 18 | 11 | 9 | 15 | 50 | 60 |
| Ice rinks (leakage reduction) | 14 | 8 | 1 | 1 | < 10 | 10 |
| Professional kitchens (leakage reduction) | 15 | 9 | 2 | 3 | 10 | 10 |
| Transport refrigeration (leakage reduction) | 9 | 6 | 1 | 2 | 10 | 10 |
| Stationary air conditioning (indirect NH ₃ -/HC-system) | 48 | 34 | 48 | 104 | 90 | 260 |
| Stationary air conditioning (leakage reduction) | 41 | 28 | 20 | 54 | 60 | 160 |
| Mobile air conditioning (CO ₂ -system) | 21 | 16 | 29 | 48 | 120 | 210 |
| Mobile air conditioning (enhanced HFC-134a-system) | 6 | 5 | 7 | 11 | 110 | 140 |
| Electrical equipment (enhanced recovery) | 2 | 1 | 1 | 1 | 20 | 40 |
| TOTAL | | | | | | |
| Reduction scenario 1 | 43 ⁷⁾ | 29 ⁷⁾ | 348 | 654 | 830 | 1 470 |
| Reduction scenario 2 | 13 ¹¹⁾ | 10 ⁷⁾ | 145 | 254 | 780 | 1 140 |

⁷⁾ Average cost effectiveness (weighted by emission reduction potential).

first Kyoto commitment period (fig. 2). Full abatement potential of scenario 2 could almost be achieved at that time, so it allows some 50% reduction also in 2020. Because options based on alternative gases and technologies were applied to new systems only, emission reductions begin to take place somewhat more slowly, but shall finally go down to 35% of the baseline in 2020 (fig. 2).

Options included in reduction scenario 1 were significantly more costly compared to scenario 2. Av-

erage costs weighted by reduction potential were 43 and 13 €/t CO₂ eq. for reduction scenario 1 and reduction scenario 2, respectively (see table 1).

According to Lehtilä and Tuhkanen (1999), implementation of several technical measures to reduce CO₂, CH₄ and N₂O emissions in Finland down to 1990 level would entail average costs of 15 €/t CO₂ eq. Leakage reduction compares to these measures as equally cost effective, whereas alternative gases and technologies are more costly.

3.5 Perspective of companies

Adoption of an emission reduction option may have an economic influence on many different types of companies. The impact may be negative or positive, and is principally directed to the enterprise that adopts the option. However, there are typically secondary companies that are associated with the situation as well.

Different types of enterprises relevant to this examination are manufacturers, importers, contractors, service and waste management companies as well as enterprises that use products or equipment that give rise to emissions. Implementation of a certain emission reduction option may have economic influence on all of these types of enterprises, although it would be focused on one type only. In addition, it is complicated to define the direction of impact for each, as well as the situation between competitors after adoption.

In this study, we didn't recognise new emission abatement technologies that would have been developed in Finland. In fact, many of the measures were originally developed by foreign or multinational companies, because of industry producing emissions of fluorinated gases is relatively small in Finland. In addition, many of the examined new technologies for air conditioning especially are more potential to be introduced in Finland than in many other countries, due to cool climatic conditions of Finland. This is because of the short season during which cooling is required, following that energy efficiency is less critical a factor compared to warmer climates.

4 Conclusions

The principal objective of the project was to gather information on emission reductions concerning emissions of HFCs, PFCs and SF₆. Abatement options were considered generally, but quantitative analyses were focused on Finland. An important part of the study was to examine the influence of reduction measures on other greenhouse gases, in order to recognise cost effective options to reduce overall greenhouse gas emissions.

In 1999, contribution of HFCs, PFCs and SF₆ was approximately half a percent of total Finnish emissions included in the Kyoto Protocol. This share is projected to increase to some 2% during the first Kyoto commitment period.

Currently, as well as in the long run, HFC-emissions due to refrigeration and air conditioning proved to be the key emission source of fluorinated gases in Finland. Thus, most part of the emission reduction potential is connected with leakage of refrigerants coming mainly from commercial and industrial refrigeration as well as stationary and mobile air conditioning systems. These emissions can be mitigated relatively cost effectively to some extent by implementing additional containment measures. Larger reductions in emissions could be achieved using alternative refrigerants and technologies, but their applicability and cost effectiveness is lower.

If recovery of HFC-refrigerants at disposal of refrigeration and air conditioning systems were not to be implemented at all, emissions according to the baseline would increase some 15% in 2010 and some 30% in 2020. However, cost effectiveness of evaluated emission reduction options would be better in that case. The situation represents a complexity of assumptions and inclusion of regulatory and technological changes in scenarios.

Basic parameters may be associated with high uncertainty. For instance, emission factors are often based on expert judgement, as opposed to direct measurement data. Systematic sensitivity analysis indicate that the primary sources of uncertainty are emission factors, as well as cost and activity data (Oinonen and Soimakallio 2002).

Further examination should include verification of emission factors and activity data, as well as cost data and applicability of the reduction options. In addition, research concerning direct refrigerant emissions and indirect emissions due to energy consumption should be integrated to establish the best options to reduce total emissions. Attention should also be paid to all other emission sources of HFCs, PFCs and SF₆, which are potentially connected to similar indirect emissions.

Publications and reports made under the project

Oinonen, T., Soimakallio, S. 2001. HFC- ja PFC-yhdisteiden sekä SF₆:n päästöjen tekniset vähentämiskeinot ja niiden kustannukset Suomessa. [*Technical and Economic evaluation of Emission Abatement Options of HFCs, PFCs and SF₆. The Case of Finland. (in Finnish, with English abstract)*]. Technical Research Centre of Finland, VTT Research Notes 2099. Espoo 2001. 154 p. + App. 17 p.

Oinonen, T., Soimakallio, S. 2002. Abatement Options and Costs of Reducing HFC, PFC and SF₆ Emissions in Finland. In: van Ham J., Baede A., Guicherit R., Williams-Jacobse J. (eds). Non-CO₂ Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects. Pp. 421–426. Millpress, Rotterdam Netherlands 2002. 714 p.

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Lehtilä, A., Savolainen, I., Tuhkanen, S. 1997. Indicators of CO₂ Emissions and Energy Efficiency: Comparison of Finland with Other Countries. Technical Research Centre of Finland, VTT Publications 328. Espoo 1997.

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The Role of Waste Management in the Reduction of Greenhouse Gas Emissions

Jätehuollon toimenpiteiden merkitys kasvihuonekaasupäästöjen vähentämisessä

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Abstract

The scope of this study was to study the reduction potential of greenhouse gas (GHG) emissions in the Finnish waste management systems. The project consisted of three sub-projects focused on energy recovery, landfill gas emissions and material recycling. Projects were carried out in co-operation with researchers from VTT and Finnish Environment Institute.

According to the Good Practice Guidelines for National GHG Inventories published by the Intergovernmental Panel on Climate Change (IPCC) in 2000 so-called First Order Decay (FOD) method will be taken into use in the Finnish landfill emission inventories in the following years. This method produces a emission profile which is more realistic than a profile produced with so-called mass balance method. Countries had earlier a possibility to choose which method is used in emission inventories but these new guidelines obligate to use the FOD method especially when there are large changes in the waste flows. In this study the emissions were estimated by using the FOD method.

According to the results significant reductions in the Finnish GHG emissions can be achieved with the help of waste management options. About 1 Mt CO₂ eq. reduction can be achieved by decreasing the amount of disposed waste by 2010 when compared to the 1990 level. By increasing landfill gas recovery about 0.6 Mt CO₂ eq. reduction could be achieved at maximum. This means that the current recovery capacity should be tripled. In addition,

emissions can be decreased about 2 Mt CO₂ eq. by increasing the utilisation of wastes (i.e. material recycling and waste-to-energy). These measures would together account for about 25% of the total emission reduction needed to fulfil the commitments of the Kyoto Protocol in Finland.

Waste management options are often very cost-effective measures to reduce GHG emissions because many measures reduce both methane emissions from landfills and CO₂ emissions from energy production and use. Therefore, waste management options should be taken into account seriously in the portfolio of Finnish GHG mitigation options.

Tiivistelmä

Tutkimuksessa selvitettiin jätehuollon toimenpiteiden mahdollisia vaikutuksia Suomen kasvihuonekaasupäästöjen vähentämiseksi. Tutkimus koostui kolmesta alaprojektista, jotka keskittyivät jätteen energiakäytön, kaatopaikkakaasujen ja materiaali kierrätyksen vaikutuksiin. Tutkimukseen osallistui useita tutkijoita VTT:ltä ja Suomen ympäristökeskuksesta.

Suomen kaatopaikkojen metaanipäästöjen arvioinnissa tullaan hallitustenvälisen ilmastopaneelin (IPCC) vuonna 2000 ilmestyneiden ohjeiden mukaisesti siirtymään nykyisestä massatasemenetelmän käytöstä päästöjen aikakäyttämisen huomioivaan laskentamenetelmään, joka kuvaa päästöjen kehittymistä huomattavasti realistisemmin. Aiemmin maat ovat voineet valita kumpaa laskentamenetelmää käytetään, mutta nyt uudet ohjeet velvoittavat käyttämään tätä ns. dynaamista menetelmää, jos jätehuollossa tapahtuu tai on tapahtunut muutoksia. Tässä projektissa päästöjen kehitystä arvioitiin dynaamisella menetelmällä.

Jätehuollon toimenpiteillä voidaan saavuttaa varsin merkittäviä kasvihuonekaasupäästöjen vä-

henemiä. Vuoden 1990 tasoon verrattuna kaatopaikkasijoituksen vähentämisellä voitaisiin enimmillään saavuttaa noin 1 Mt CO₂-ekv. Päästöjen vähenemä vuoteen 2010 mennessä. Kaatopaikka-kaasujen talteenoton lisäämisellä pystyttäisiin lisäksi vähentämään päästöjä käytännössä enimmillään noin 0,6 Mt, mikä merkitsisi talteenottokapasiteetin kolminkertaistamista nykytasolta. Jätteiden hyötykäytön (materiaalikierrätys ja energiakäyttö) lisäämisellä pystyttäisiin edellisten lisäksi vähentämään päästöjä enimmillään noin 2 Mt. Yhteenlaskettuna nämä vastaisivat noin neljäsosaa kansallisessa ilmastostrategiassa arvioidusta päästöjen vähentämistarpeesta vuonna 2010.

Kustannuksiltaan jätehuollon toimenpiteet ovat vähennettyjä päästöjä kohti usein hyvin edullisia, koska monet toimenpiteet vähentävät yhdenaikaisesti sekä kaatopaikkojen metaanipäästöjä että energian tuotannosta ja käytöstä aiheutuvia hiilidioksidipäästöjä. Täten jätehuollon toimenpiteisiin tulisi kiinnittää myös jatkossa erityistä huomiota,

kun tarkastellaan Suomen kasvihuonekaasupäästöjen vähennystoimenpiteiden valikoimaa.

1 Introduction

Intergovernmental Panel on Climate Change (IPCC) has published “good practice guidance” for national greenhouse gas inventories in 2000 (IPCC 2000), according to which also the assessment of methane emissions from Finnish landfills will be changed from present mass balance based method to “first order decay method, FOD”. This method estimates emissions more realistically, especially when changes in the composition of waste are going to happen. Earlier each state has had the possibility to choose which method they use, but the new guideline obliges to the use of FOD method especially if changes in the composition of the waste has happened or is assumed to happen in the near future. In Finland the landfill disposal has significantly decreased in the 1990’s and FOD method should be used. Methane emissions from landfills

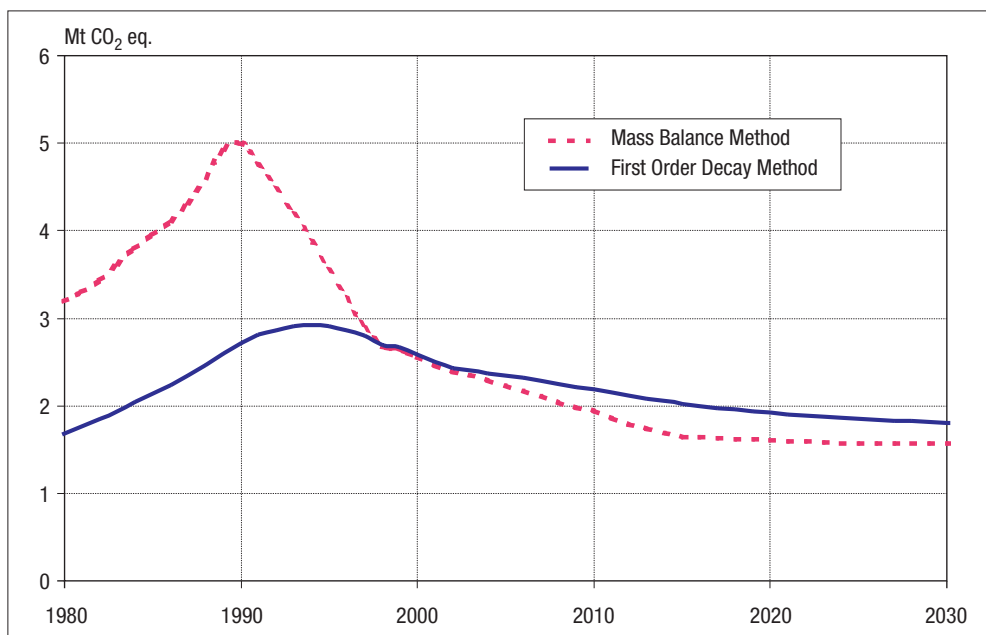


Figure 1. Estimated methane emissions from landfills based on “Business as usual” scenario by Finnish Environmental Institute (Dahlbo et al. 2000). Calculations are made with both mass balance method and FOD-method.

calculated with both models are described in Figure 1.

The first estimations based on FOD-method show that methane emissions would have been at a same level in 2000 as in 1990. Mass balance based method shows a decrease of 2.5 Mt CO₂-equiv. at the same time period. Mass balance based estimations about the decrease of methane emissions are thus mainly theoretical because of the slow decomposition of the waste, which cannot be assumed to happen immediately after disposal but rather takes years or decades. According to the national emission inventory for 1999, the decrease in methane emissions from landfills has been approximately 1.8 Mt (CO₂-equiv.), but new estimations made in this study show the emission level to be 30% higher and the estimated decrease thus greater than expected. If FOD-method were used, the Finnish total GHG emissions would change from 77.1 Mt CO₂-equiv. to 76.0 Mt CO₂-equiv. in 1990 and from 76.2 Mt CO₂-equiv. to 77.2 Mt CO₂-equiv. in 1999.

If compared to the national climate strategy, even 2 Mt CO₂-equiv. extra reduction in GHG emission level is demanded for other sectors than waste management if FOD-method is used in the estimation of landfill based emissions. Calculated with the average reduction costs approximated in the national climate strategy (30–60 €/t CO₂-equiv) the annual direct costs without taxes would be approximately 60–120 million euro.

Historical information about the disposed waste and degradation rates of different waste fractions is also needed in emission inventories based on FOD-method. This causes extra challenge because practically statistical data about neither the composition nor the amount of waste disposed is available before the year 1990. The estimations must thus be done based on different kinds of indicators, i.e. population, industrial production and GDP, which is also acceptable according to the IPCC calculation principles. Additionally no domestic data on degradation periods is available, and default values published by IPCC must be used at least in the first estimates.

2 Landfill gas recovery

In this study, methane emissions from landfills were estimated in three different scenarios:

- “present development” scenario, in which the amount of landfill disposed waste equals with “present development” scenario by the Finnish Environmental Institute
- “National Climate strategy” scenario, in which the amount of landfill disposed waste equals with “combustion/gasification” scenario by the Finnish Environmental Institute
- “Zero organics in 2010” scenario, in which it is assumed that no organic waste is disposed to landfills in 2010. The linear decrease in disposed organic waste starts in 2002.

Estimated CH₄ emission decrease is about 0.5–1.0 Mt CO₂-equiv. from 1990 to 2010 calculated with FOD method (figure 2), when only the decrease in landfill disposed waste is considered. The decrease of 1.0 Mt CO₂-equiv. would additionally demand the total prohibition of landfill disposed organic (biodegradable) waste until year 2010 and minimisation activities should begin in the near future. Practically this means a significant increase in material recycling, biodegradable waste treatment and energy recovery.

According to our estimates it is possible to triple landfill gas recovery from current level and to decrease the amount of methane emissions by about 0.4–0.6 Mt CO₂-equiv. by 2010. The amount of landfill gas collection sites would thus rise from 20 to 50. Estimated annual electricity produced by energy recovery of the gas is 65–105 GWh, and reduction in GHG emissions maximum of 0.05 Mt CO₂-equiv.

Later on in the future, landfill gas production is going to decrease if disposal of organic waste is decreased. Further additional decrease in the amount of landfill-based greenhouse gas emissions would most probably require oxidation of methane on the surface of the landfill. These kinds of solutions are also applicable to small sites. Rough estimates about GHG emission reduction potential of this measure are between 0.1 and 0.2 Mt CO₂-equiv. in 2010. Figure 2 presents the estimated methane

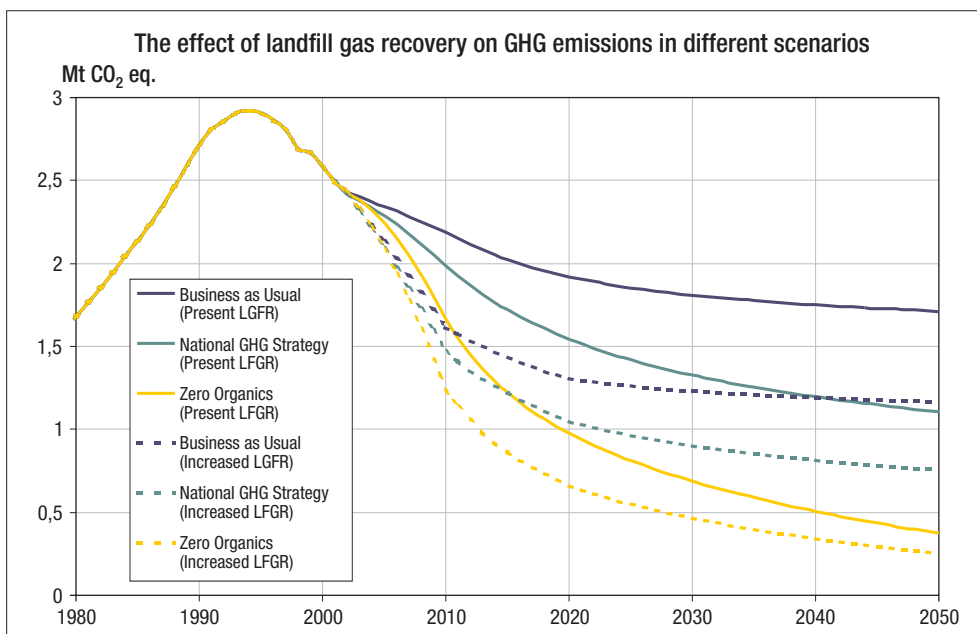


Figure 2. Methane emissions from landfills in different scenarios and the influence of increased landfill gas recovery. Influence of gas treatment on the surface layer is not included. LGFR=landfill gas recovery

emissions from landfills and the difference between the selected scenarios.

Estimated costs indicate that landfill gas recovery is quite economical a way to minimise GHG emissions if compared to e.g. costs estimated in national climate strategy. If recovered gas is flared in a torch, the estimated emission reduction costs are about 2.5–5.0 €/t CO₂-equiv. With energy recovery the costs are probably lower, and in some cases actually negative. Estimated costs due to oxidation on the surface of a landfill on small sites are about 15–20 €/t CO₂-equiv., which also seems to be quite reasonable.

3 Material recycling

Recycling rates are already quite high for many materials. In this part of the study the possibilities and potential for increasing the recycling rate were estimated and the greenhouse gas emission reduction potential calculated.

The focus was on three kinds of materials.

- The materials, which require lots of (fossil) energy sources when produced from virgin raw materials. By recycling these materials, the emissions from energy production can be reduced when recycling processes are less energy intensive.
- The materials, which produce direct GHG emissions in their production processes.
- The materials, which produce emissions in their disposal or treatment processes, eg. land filling of bio-waste.

In this part of the study, the potential greenhouse gas emissions from recycling of packaging waste, paper and fibres, bio-waste, waste from electric and electronic equipment (WEEE) and waste from scrap vehicles and tyres are considered.

3.1 Treatment of bio-waste

One of the key elements in reducing greenhouse gas emissions from landfills is bio-waste, as it almost totally consists of organic matter, which

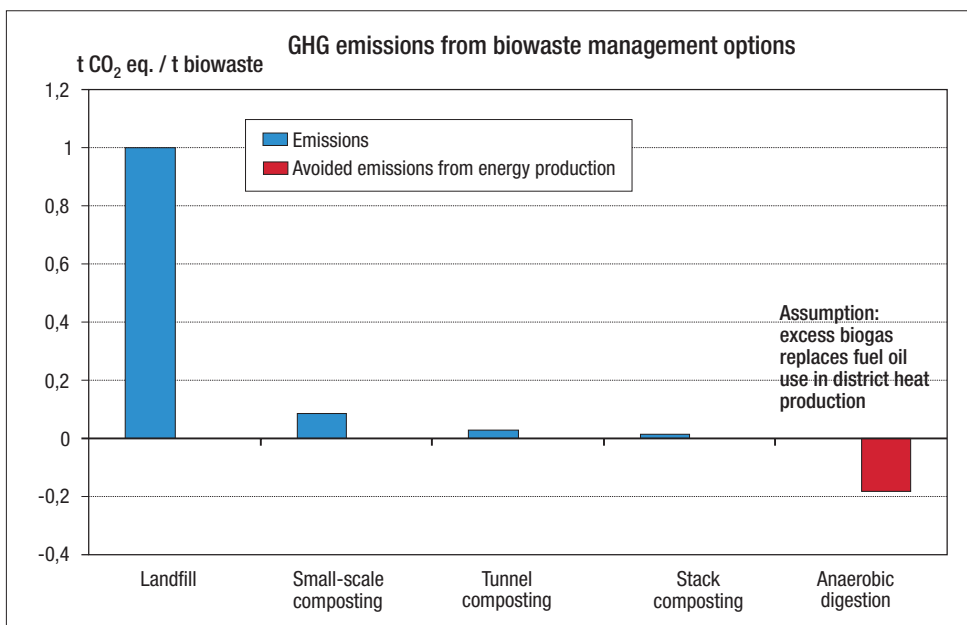


Figure 3. Estimated greenhouse gas emissions from the treatment of bio-waste. Process-related emissions and emissions from the energy production are considered in composting and anaerobic digestion. Avoided emissions from energy production are also included in anaerobic digestion.

forms methane when degraded in anaerobic circumstances. Furthermore, the share of bio-waste in the total waste amount is quite remarkable. Currently biological waste is disposed or composted and in small amounts digested in anaerobic reactors in Finland.

Figure 3 illustrates the GHG emissions from the bio-waste management options. As it can be seen, composting is a relatively efficient way to reduce GHG emissions if compared to landfill disposal. Some minor methane emissions might anyhow come from composts if they are not properly maintained and waste is not kept in aerobic circumstances. To avoid this e.g. in tunnel composts, auxiliary air is blown from underneath the waste, which requires a little amount of electricity and indirect GHG emissions.

In the anaerobic digestion process, waste is kept in a closed reactor in an optimal environment for methane generation. This is why the methane emissions from the digestion process are avoided. Produced and recovered amount of biogas is ap-

proximately 3.5 GJ/ton bio-waste, calculated in energy terms (Pipatti et al. 1996). Some of this energy is used in the process and the rest can be used in the production of e.g. external electricity and/or district heat. Anaerobic treatment is thus most favourable option for bio-waste treatment in terms of greenhouse gas emissions, because process emissions are avoided and energy content is recovered.

3.2 Other materials

To estimate greenhouse gas emissions from material recycling the following materials were assessed: paper and cardboard, glass, steel, aluminium and plastics (mainly polyethylene). Also the recovery of slag was included in the estimation of greenhouse gas reduction potential.

Estimated GHG emission reduction potential, which is achieved by increasing the recycling rates for studied materials, is 0.5–1 mill. tons of CO₂ equivalents by year 2010. Calculations are based on estimates on emissions and energy consumption in material production and recycling pro-

cesses. Recycling and recovery targets from present and prepared EU-directives and national legislation were used as a basis for calculations. Most targets do not extend beyond the year 2005, and at the minimum scenario it is assumed that they are not going to increase. At the maximum scenario recycling targets are increased step by step by year 2020. The lack of information of GHG emissions from the recycling and manufacturing processes complicates the estimations. Also shares of materials are very difficult to get from the current waste statistics, which are mainly named after either products or industrial processes.

GHG emission reduction potential from material recycling is separated to small and inhomogeneous material flows. The largest individual reduction is the utilisation of industrial slag in the production of cement (max. 0.5 mill. tons of CO₂-equiv. by 2010). The recycling of construction and demolition waste can be more effective and also the recycling rates of paper, packages and metal scraps can be increased. The recycling rates for waste from electric and electronic equipment are set quite low in the beginning, and the estimates of the amount of waste are quite uncertain.

Material use in the future has a significant impact on the composition and amount of waste as well as on material applicability for recycling. *Dematerialization* in the society, i.e. decreasing the material end energy inputs in industrial and societal processes, decreases the amount of waste in general, but technically this kind of development might end up to light weighted polymer-based composites that substitute currently used materials like steel and glass. Especially because of their technical design, these kinds of materials are difficult to be recovered and/or recycled. Global markets for products and materials complicate the material recycling. Economically operative recycling processes are difficult to create and maintain if used products are to be recycled for new products (i.e. closed-loop recycling). One trend in the future is also the use of biologically degradable raw materials like paper fibres to substitute plastics as raw materials. Even though the use of renewable materials is not limited, the generated amount of waste is significant. Increased transport distances both in global recycling systems and renewable materials can in

many cases, especially in terms of GHG emissions, reduce or even neutralise the benefits from the system.

4 Energy recovery

According to the national waste plan until 2005, the waste recovery degree in municipalities is to be increased from current 40% to 70% by year 2005. Meeting the goal requires a considerable increase in energy recovery, since with current prices the goal cannot be met by increasing only material recycling. Recovered fuels (REF) are not necessarily required in the energy sector because the requirements of RES-E directive can be fulfilled with the use of wood. However, utilisation of recovered fuels in energy production offers an economical way to reduce the amount of waste on landfills and to recover combustible materials, which are unqualified for material recycling. The production and energy recovery of REF will require new manners of action and co-operation not only from the technical point of view but also in the entire waste management chain including the local authorities. The Finnish waste treatment system based on source separation is presented in Figure 4, the current production and treatment of municipal solid waste in figure 5 and the vision of upcoming reach of the goal at the Helsinki metropolitan area in figure 6.

Current use and production of recovered fuel as well as needs for technology development to fulfil the requirements of waste incineration directive has been considered in the report of energy recovery sub-project (Lohiniva et al. 2002). Current annual amount of energy recovery is about 300 000 tons of commercial and industrial packaging waste and additionally 20–50 thousand tons of REF III from households and municipal waste at the incineration plant in Turku. Dominating techniques at the moment are incineration of mixed municipal waste (mass burning), co-combustion in fluidised bed combustion plants and co-firing by gasification. New investments in flue gas cleaning equipment is needed before year 2005, when EU directive on waste incineration will be applied in all existing plants that use waste fuels. Evidentially most of our present practices on REF utilisation are then coming to an end. In addition to energy technology

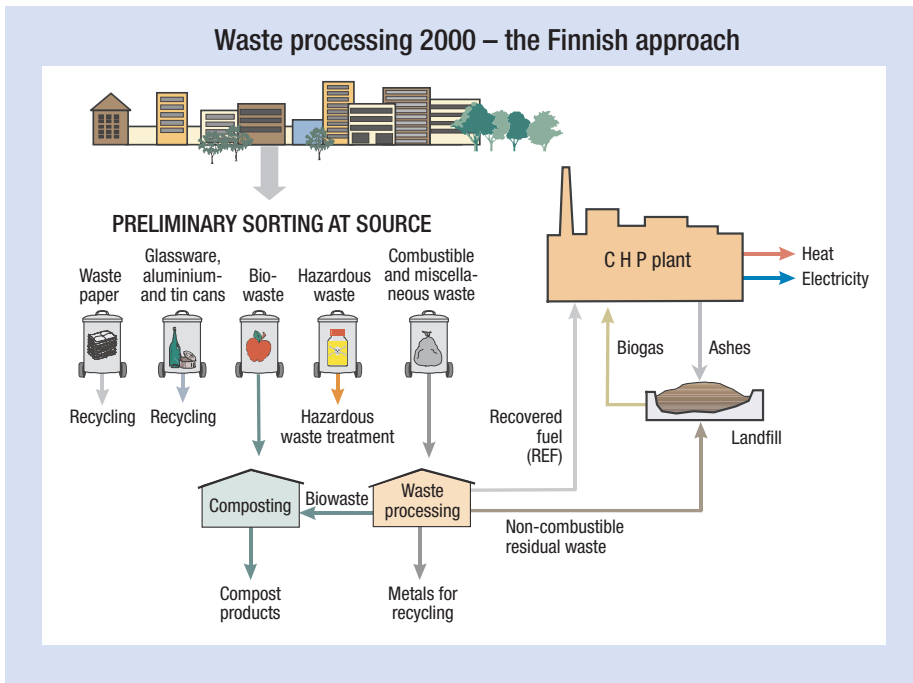


Figure 4. The Finnish waste treatment system based on source separation maximises opportunities for material recycling and energy production.

there is also a great challenge of adding some 0.6–1.5 Mt recycled fuel (15–30 PJ primary energy) annually into our current CHP systems without changing current structure and costs of combined heat and power production. District heat markets are already considered as saturated and new investments on district heating capacity and REF combustion plants will mainly be made when old plants are replaced. Typical lifetime of a power plant is between 30 and 40 years.

Energy recovery both in 2005 and vision to year 2010 is described in more details in the report (Lohiniva et al. 2002). The vision for the year 2010 is based on the option in which the disposal of any combustible or biodegradable waste to landfills would be forbidden. This kind of banning came into force in the beginning of year 2002 in Sweden. Figure 7 illustrates the waste-to-energy capacity options if the ban for organic waste landfill would be stated in Finland. New plants – based e.g. on fluidised bed combustion or gasification - utilising REF could be built next to or to replace existing

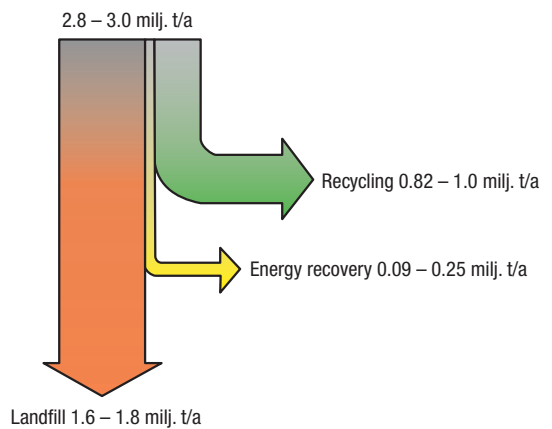


Figure 5. Production and treatment of municipal solid waste in Finland.

plants in 20 Finnish cities. Both biofuels and REF in quality classes REF I-III can be used in these new boilers to substitute e.g. coal. Finnish leading knowledge on the area of fluidised bed combustion and gasification can be used to create a new com-

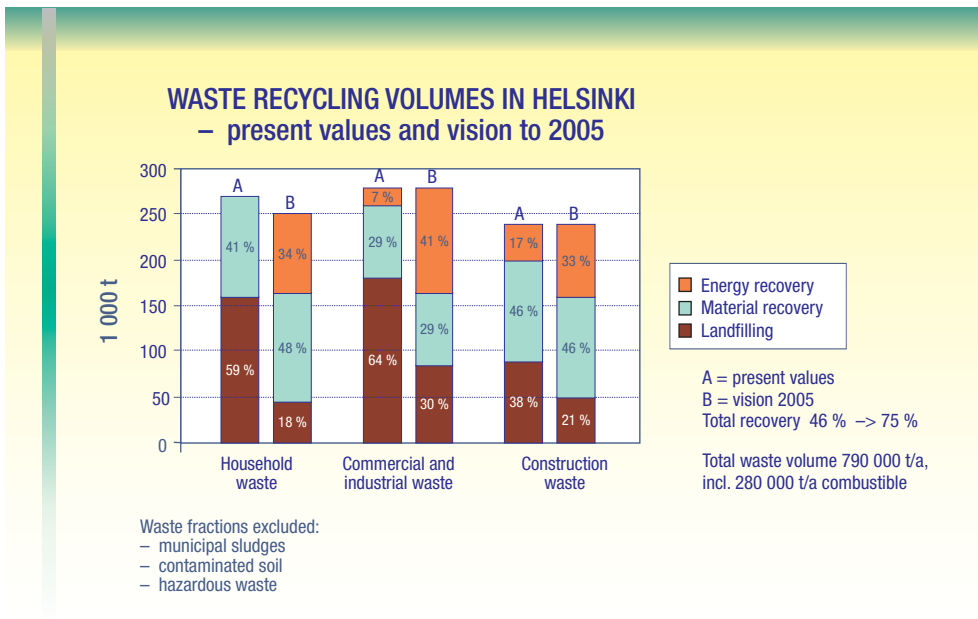


Figure 6. Current production of municipal waste at Helsinki metropolitan area and vision for the year 2005.

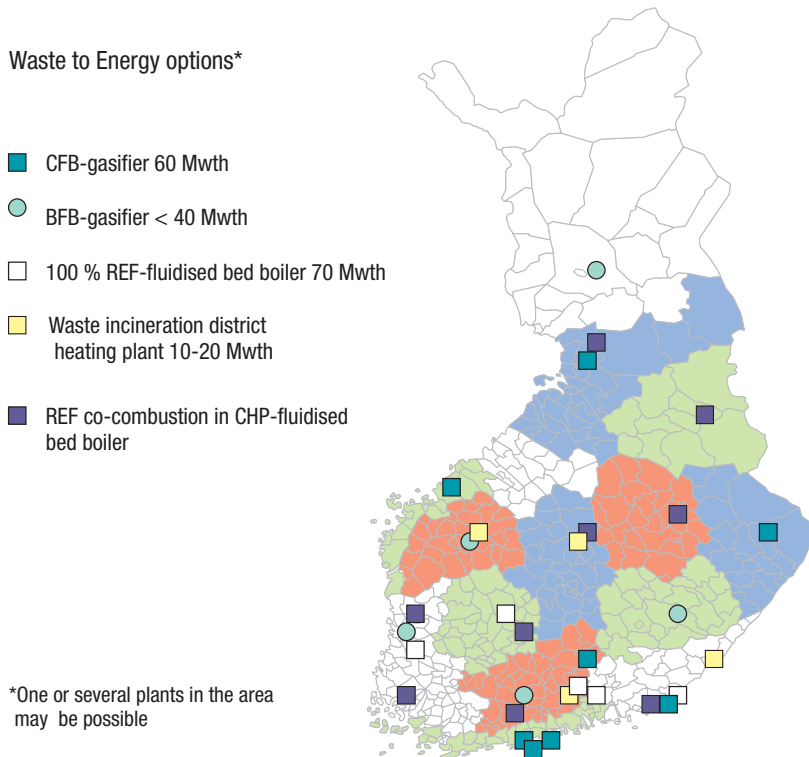


Figure 7. Energy recovery options in Finland, if landfill of organic waste is banned.

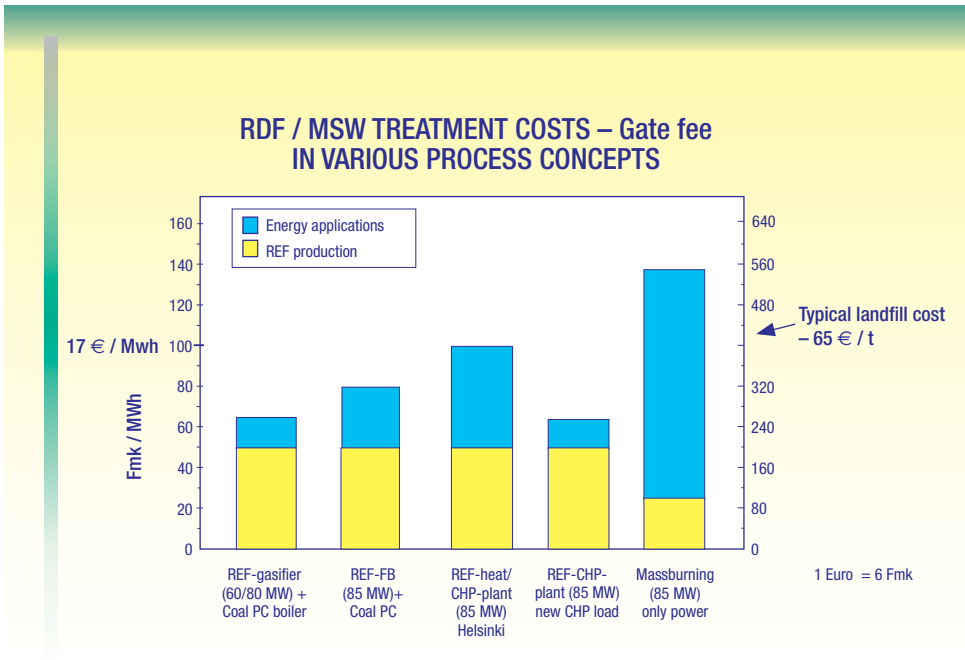


Figure 8. The costs of energy recovery are lower than landfill charges with taxes.

petitive technology for REF combustion to avoid more expensive municipal waste incineration plants, which are traditionally used in the Central Europe. All the new technical solutions must fulfil the requirements of EU directive on waste incineration as well as the one for large-scale combustion plants. Some special issues concerning e.g. REF gasification and nitrogen and sulphur emissions from the main boiler are to be decided in 2002 or 2003.

The main topic in this study has been the description of rational criteria between material recycling and energy recovery of combustible waste. Directions of the authorities give guidelines on this e.g. by binding EU directives concerning e.g. packaging waste, waste from scrap vehicles and electric and electronic waste. The national waste plan to 2005 sets a target for municipal waste recovery to 70%, fulfilling of which requires significant energy recovery of waste which is unqualified for material recycling. Examples of REF energy recovery costs are presented in Figure 8. Unfortunately, in public discussion, and to a certain extent in National Waste Plan, material recycling and en-

ergy recovery are considered as opposed and exclusionary to each other, although they should rather be seen as supportive to each other. The most important measures of authorities to realise the recovery target of National Waste Plan are amount of landfill taxes and harmonising of landfilling fees.

Recovered fuels are mainly composed of paper and cardboard, different kinds of plastics and wood and additionally of non-combustible parts like glass, metals, cans and minerals. In Finland the main research area has been so called “Finnish model” (Figure 4), in which centralised treatment of waste takes place at the REF production site where recyclable materials, combustible materials and foreign matter are mechanically separated and different quality of REF is produced. Some sites are already in operation, but the development is still ongoing and results from the long-term tests of demonstration plants are not yet gathered. Additionally, the separation of fibres and plastics has been studied in so called “Urban Mill” concept, in which a paper mill using recycled fibres is integrated as a part of the municipal waste treatment and energy production services. The annual in-

crease of fibre recycling from packaging waste has been approximated to be 100 000 tons annually if three Urban Mill plants are to be sited in the Southern Finland.

Energy recovery from waste would take place mainly in the same boilers as the additional use of wood as a fuel. This interaction has been taken into account while performing the studies in the Climtech projects published in the following publications (Lohiniva et al. 2002, Helynen et al. 2002). Wood waste and combustible municipal waste are locally generated in different areas. The greatest decrease of GHG emissions is achieved when fossil fuels (oil, coal or peat) are substituted in present or new boilers. It has been assumed that energy recovery from waste mainly substitutes coal and in a few cases peat. Competition with wood is very rare. The national programme for the promotion of renewable energy sources sets a target to the increase in the use of bio-energy by 2.3 Mtoe/a from 1995 level by 2010 and the use of REF 0.5 Mtoe/a at the same period. In Climtech projects the estimated additional biomass use by 2010 is between 1.2 Mtoe/a (base case) and 3 Mtoe/a (maximum case). Thus, the decrease in GHG emissions would be 2.8–10.9 Mt CO₂/a, and additional decrease from waste management 1.5–3.6 Mt/a. Costs would be quite reasonable and mainly less than 20 €/t CO₂.

5 Conclusions and discussion

Estimates of GHG reduction potentials are summarised in table 1. By minimising the landfill disposal it is possible to achieve the maximum reduction of 1 Mt CO₂-equiv. from 1990 to 2010 (see also figure 2). Additional reduction of 0.6 Mt can be achieved by the recovery of landfill gases, which means that the amount of gas recovered is tripled from the current level. With waste recovery (material recycling and energy recovery) the maximum decrease of GHG emissions is 2 Mt.

In the recovery scenario in table 1 three Urban Mill plants are built in Southern Finland and additional 100 000 tons of fibres are recycled. This amount of fibres would be used in the paper industry instead of energy production, and emission reduction potential in material recycling would increase and respectively decrease in energy recovery. However, net emission reduction potential would be constant in this case.

Costs per reduced ton of GHG emissions of the actions in waste management are usually quite reasonable, because many of the actions simultaneously reduce emissions from landfills, from energy production and use. Therefore, specific attention must be drawn to the waste management options in the future when national action for the reduction of GHG emissions is considered.

Table 1. Estimated decrease of greenhouse gas emissions in waste management in different scenarios in 2010 (calculated from 1990 emission levels).

| Action [Mt CO ₂ -eq.] | Business as usual | Climate strategy/ landfill-directive | Prohibition of organic waste on landfills 2010 | Recovery |
|--|-------------------|--------------------------------------|--|------------|
| Decreasing of landfill waste | 0.5 | 0.7 | 1.0 | 1.0 |
| Recovery of landfill gases and increasing the use of surface solutions | 0.6 | 0.6 | 0.5 | 0.5 |
| Increasing energy recovery (substitution of fossil fuels) | 0.2 | 0.6 | 1.5 | 1.0 |
| Increasing of material recycling (substitution of primary materials by recycled materials and energy saving) | 0.2 | 0.4 | 0.6 | 1.1 |
| Total | 1.5 | 2.3 | 3.6 | 3.6 |

Publications and reports made under the project

Lohiniva, E., Sipilä, K., Mäkinen, T., Hietanen, L. 2002. Jätteiden energiakäytön vaikutukset kasvihuonekaasupäästöihin. [Waste-to-energy and greenhouse gas emissions]. Espoo: VTT. (VTT Research Notes 2139). In Finnish, English abstract. <http://www.inf.vtt.fi/pdf/tiedotteet/2002/T2139.pdf>

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Lohiniva, E., Sipilä, K., Mäkinen, T., Hietanen, L. 2002. Jätteiden energiakäytön vaikutukset kasvihuonekaasupäästöihin. [Waste-to-energy and greenhouse gas emissions. (In Finnish, with English abstract)]. Espoo: VTT. (VTT Research Notes 2139). <http://www.inf.vtt.fi/pdf/tiedotteet/2002/T2139.pdf>

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