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Integrated cost-effectiveness analysis of greenhouse gas emission abatement

The case of Finland

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Abstract

In Finland greenhouse gas emissions are expected to increase during the next decades due to economic growth, particularly in the energy intensive industrial sectors. The role of these industries is very central in the national economy. The emission control according to the Kyoto Protocol will therefore be quite difficult and costly.

The study analyses the cost-effectiveness of different technical options for reducing the emissions of carbon dioxide, methane, and nitrous oxide in Finland. The analysis is performed with the help of a comprehensive energy system model for Finland, which has been extended to cover all major sources of methane and nitrous oxide emissions in the energy sector, industry, waste management and agriculture. The focus being on technical options, no consideration is given to possible policy measures, emission trading or joint implementation in the study.

Under the boundary conditions given for the development of the Finnish energy economy, cost-effective technical measures in the energy system include increases in the use of wood biomass, natural gas and wind energy, increases in the contribution of CHP to the power supply, and intensified energy conservation in all end-use sectors. Additional cost-effective measures are landfill gas recovery, utilisation of the combustible fraction of waste and catalytic conversion of N_2O in nitric acid production. With baseline assumptions, the direct annual costs of emission abatement are calculated to be about 2000 MFIM (330 M∈) in 2010. The marginal costs are estimated to be about 230 FIM (40 ∈) per tonne of CO_2-equivalent in 2010. The cost curve derived from the analysis could be used in further analyses concerning emissions trading.

Preface

In Kyoto in 1997 practically all the nations of the world agreed on a greenhouse gas abatement protocol limiting the emissions from the industrial countries. The reduction of the greenhouse gas emissions is a challenging task as the growth of the economy tends to increase the energy demand. This study considers the technical possibilities and costs of reducing the Finnish emissions of the three most important greenhouse gases: carbon dioxide, methane and nitrous oxide. Especially cost-effective solutions of emission reduction are searched for.

The work has been carried out at VTT Energy as a part of the Energy and Environment Research Programme SIHTI 2 of the Technology Development Centre of Finland (Tekes). Additional funding has been obtained from the Ministry of Environment. The chairman of the SIHTI 2 steering group was Mr. Heikki Niininen of Fortum Ltd. and the contact person in the Ministry of Environment, Mr. Seppo Sarkkinen. Dr. Ilkka Savolainen of VTT Energy acted as project leader, and Messrs. Antti Lehtilä and Sami Tuhkanen of VTT Energy as research scientists.

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APPENDICES

1. Introduction

Anthropogenic emissions are increasing the atmospheric concentrations of several important greenhouse gases. In the Kyoto Protocol in 1997 the parties of the UN Framework Convention on Climate Change (FCCC) agreed on strict limits for greenhouse gas emissions from industrialised countries. To compensate for annual fluctuations of the emissions, the average over a five-year period in 2008–2012 is used for monitoring the emission levels. The protocol deals with emissions of carbon dioxide, methane, nitrous oxide, and three types of fluorinated gases. The emission targets agreed upon are related to the total aggregate greenhouse impact of all the gases pertaining to the protocol.

The emissions of the first three gases are compared to the 1990 level, and the emissions of the fluorinated gases are compared optionally either to the 1990 or the 1995 level. The emission reduction commitment of the Kyoto Protocol is valid for the GWP-weighted (see Chapter 3) sum of the gas emissions expressed in CO_2 equivalents. This enables countries to focus the emission reductions on different gases in a cost-efficient way. For example, a country could reduce methane emissions substantially if reduction of the dominant greenhouse gas, carbon dioxide, is too difficult or expensive.

According to the Protocol, countries are allowed to perform part of their commitments by increasing the sinks, i.e. by land-use change and forestry. Afforestation and reforestation done after 1990 are counted as positive actions in the calculation of national emission balances. Similarly, erasing the forests is counted as a negative action (FCCC 1997). Detailed calculation methods for the sinks are under consideration, and they will probably be added to the Framework Convention on Climate Change in forthcoming conferences of parties (COP), likely in the year 2000 or later.

Policies and measures (PAMs) for the emission reductions are mentioned in the Protocol only as suggestive and optional ones, and therefore countries are allowed to choose them without constraints or obligations. Emissions trading was also considered in the Kyoto conference, and was accepted into the protocol. The parties to the protocol may, supplemental to domestic actions, participate in emissions trading for the purposes of fulfilling their national commitments after the year 2000 (FCCC 1997). In such trading a country buys emission reduction quotas from another party to the protocol, implying that the necessary emission reductions are less costly to the seller party. In addition, joint implementation is allowed between different parties. In joint implementation emission reduction projects, or measures to increase the sinks within one party's territory will be counted to another party’s credit. Joint projects can be implemented also between industrial and developing countries under the Clean Development Mechanism. Detailed rules for emissions trading and joint implementation have not yet been accepted. The sanctions for the parties not meeting their commitments will also be considered in the forthcoming conferences of parties.

The EU commitment in the Kyoto Protocol is to reduce emissions by eight per cent from the 1990 level. The EU has shared the emission reductions between its member states in June 1998. Finland has agreed on a national commitment to return the emissions to the 1990 level. In practice, this commitment will require the implementation of quite extensive reduction measures. In 1997 the Finnish CO_2 emissions from energy use and industrial processes were already about ten per cent higher than in 1990 (Statistics Finland 1998b).

The objective of the present study is to present a comprehensive analysis on the cost-effectiveness of technical measures for reducing greenhouse gas emissions in Finland. However, only the three most important gases, carbon dioxide, methane and nitrous oxide are taken into consideration. In order to assess various technical options simultaneously and consistently, a large systems model based on cost optimisation is used. The focus of the model is on the national energy system, but modules for agriculture and waste management have been included as well

Firstly, an overview of the sources and present inventories of greenhouse gas emissions is given in Chapter 2. In Chapter 3 the methods for calculating the greenhouse effect are presented. A brief review of the various technical options available for the abatement of greenhouse gas emissions in Finland is given in Chapter 4. The calculation model and the technical measures taken into account in the study are described in more detail in Chapter 5. As the analysis is dealing with projections into the future, a number of different future scenarios have been constructed, and these will be presented in Chapter 6. Finally, the main results from the analyses are presented and discussed in Chapters 7 and 8.

2. Greenhouse gas emissions in Finland

2.1 Overview

The Kyoto Protocol covers six important types of greenhouse gases: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). Besides these, there are many other significant greenhouse gases, such as chlorinated and brominated hydrocarbons. However, because the emissions of these gases deplete stratospheric ozone, their emissions are already dealt with by other international protocols, and are usually not included in greenhouse gas balances.

The emissions of some other gases, like nitrogen oxides, volatile organic compounds, carbon monoxide, and sulphur dioxide affect indirectly the regional and local radiation balance in the atmosphere, contributing to the greenhouse effect. The impact of these emissions takes place via formation of tropospheric ozone, which has a warming impact, or aerosols, which tend to cool. The net impact of these emissions is uncertain, however (IPCC 1996a).

National inventories of greenhouse gas emissions are most reliable for carbon dioxide. Most of the emissions are due to combustion of fuels, for which reasonably accurate statistics are normally available. Furthermore, the combustion of renewable fuels such as wood biomass need not be included in the inventories if it can be assumed that the carbon released into the atmosphere will be compensated by the growth of the biomass stocks in living vegetation, litter and soils.

Over the past decade many revisions have been made to the national greenhouse gas inventories, including carbon dioxide. Regarding CO_2 emissions, the revisions have been mainly due to extended coverage of various emission sources not related to fuel combustion, but also due to refined calculations of the actual amounts of fuels combusted. However, much higher uncertainties are involved in the estimates for the other greenhouse gases.

The latest national estimates for the Finnish greenhouse gas emissions in the year 1990 and 1995 are presented in Table 1 . When all emissions are converted to CO_2-equivalents using relative coefficients of their greenhouse warming potential over 100 years' integration time, carbon dioxide accounted for about 84% of the total greenhouse impact in 1990. The combined share of methane and nitrous oxide was about 16%. Emissions of hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride are relatively small in Finland, and account for less than 0.5% of the total greenhouse impact.

Table 1. Summary of greenhouse gas emissions in Finland in 1990 and 1995, and a baseline projection until 2020 [1].

Year	1990	1995	2000	2010	2020
Carbon dioxide emissions, Tg					
Fuel combustion	53.8	55.1	61.8	70.5	78.4
Industrial processes	1.2	0.8	0.9	1.1	1.2
Fugitive emissions [2]	3.5	3.8	3.8	3.8	3.8
Non-energy uses [2]	0.6	0.6	0.6	0.6	0.6
Total CO_2	59.1	60.3	67.1	76.0	84.0
Methane emissions, Gg					
Waste management	240	161	160	160	160
Agriculture	94	81	74	71	71
Energy sector	20	21	21	23	24
Industrial processes	4	4	5	6	7
Total CH_4	358	267	260	260	262
Nitrous oxide emissions, Gg					
Agriculture	10	9	8	8	8
Energy sector	6	6	9	13	12
Industrial processes	3	3	3	3	3
Total N_2O	19	18	20	24	23
Other greenhouse gases, Mg					
HFCs	n.a.	61	100	150	150
PFCs	n.a.	0.04	0.05	0.10	0.10
SF_6	n.a.	4	5	6	6

[1] Figures are primarily based on official statistics and projections (Ministry of the Environment 1997), with some small recent revisions.

[2] No projection is available for fugitive emissions or emissions from non-energy use; the emissions are assumed to remain roughly at the 1995 level.

For several countries estimates for emissions of the new gases are still very rudimentary or not available. Nevertheless, because the relative importance of these gases is in most countries quite small, a reasonably reliable comparison of total emissions can be made between countries. In Figure 1 total greenhouse gas emissions from the six gas categories included in the Kyoto Protocol are shown for all EU countries, in terms of CO_2 equivalents (the relative weights for CO_2, CH_4 and N_2O are 1, 21, and 310, respectively; see Chapter 3).

This study considers only the emissions of carbon dioxide, methane, and nitrous oxide. In the following sections the emission estimates for these gases are presented in more detail for each of these gases and for each sector. For simplicity, all emissions from fuel combustion activities are discussed under the energy sector, even if the primary purpose of the industrial fuel combustion is not energy production.

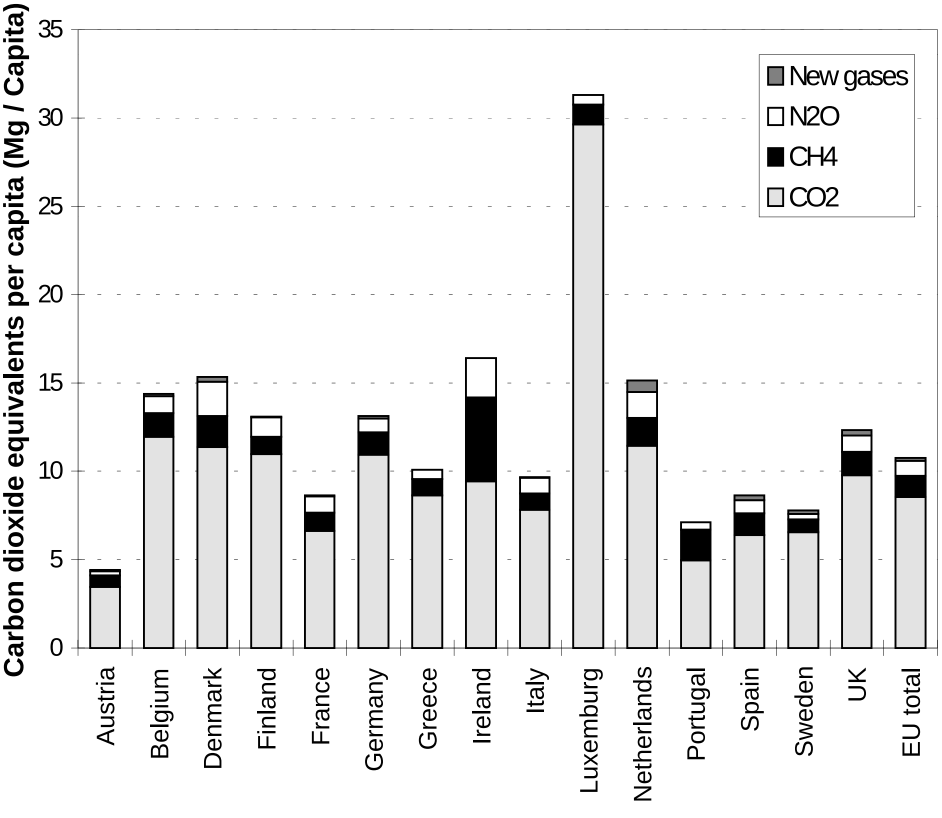

Figure 1. Greenhouse gas emissions in EU-countries in 1995 (Source: Unpublished memorandum by Jim Penman, Department of the Environment, UK). For some countries estimates for the new gases were still missing.

2.2 Carbon dioxide

2.2.1 Overview

Carbon dioxide is by far the most significant greenhouse gas, both globally and in Finland. The total amount of CO_2 emitted in 1990 has been officially estimated to be about 59 Tg (CO_2)[1]. Combustion of fuels accounted for about 54 Tg of the total CO_2 emissions, and industrial processes about 1.2 Tg. The remaining emissions were due to fugitive emissions from peat production, and from the partial oxidisation of fuels basically used for non-energy purposes (e.g. lubricants, feedstocks, etc.).

Estimates of the Finnish carbon dioxide emissions by source between 1960 and 1996 are presented in Figure 2, excluding the fugitive emissions and non-energy uses, for which estimates were available only for the most recent years.

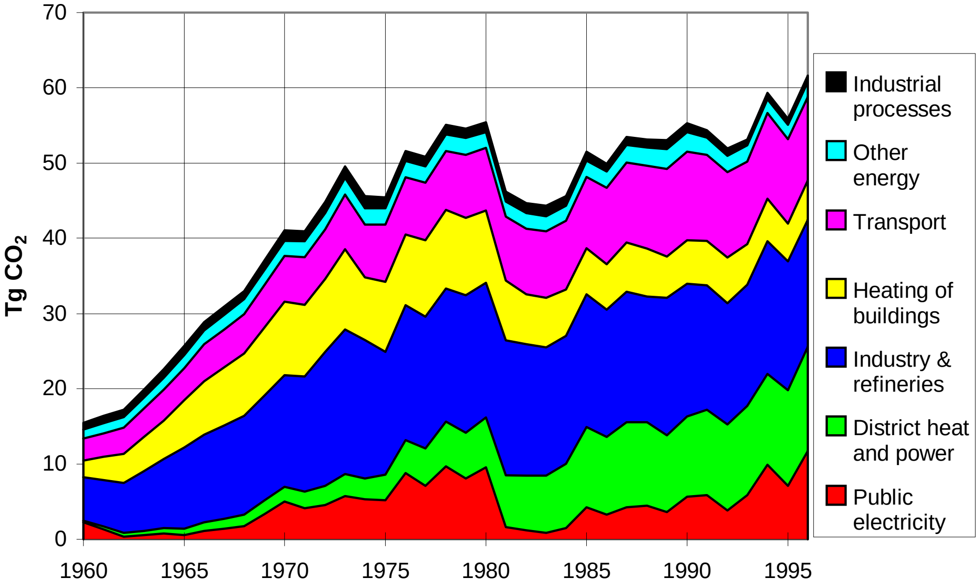

Figure 2. Development of Finnish carbon dioxide emissions between 1960–1996, excluding fugitive emissions (Lehtilä et al. 1997a).

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[1] Unpublished revised estimate made by the Ministry of the Environment, 18.6.1998.

Although the energy use in the transport sector has been steadily increasing, a clear shift from end-user sectors to the energy sector can be identified. Main factors behind the shifts are the overall electrification of the energy economy and the expanding utilisation of district heating. One should point out that in Figure 2 the emissions from industrial self-generation of electricity are included in the industrial sector.

2.2.2 Fuel combustion activities

The Finnish carbon dioxide emissions from the combustion of fossil fuels and peat are shown in Figure 3. According to the IPCC methodology, carbon dioxide emissions from biomass fuels are included in the national emissions accounts as information entries only, and are not included in the total national CO_2 emissions from fuel combustion. Furthermore, apart from wood biomass and vegetal fuels, also waste-derived fuels, such as agricultural, municipal and industrial waste and landfill gas, are classified as biomass fuels. Therefore, no emissions from waste fuels or other biofuels are included in Figure 3.

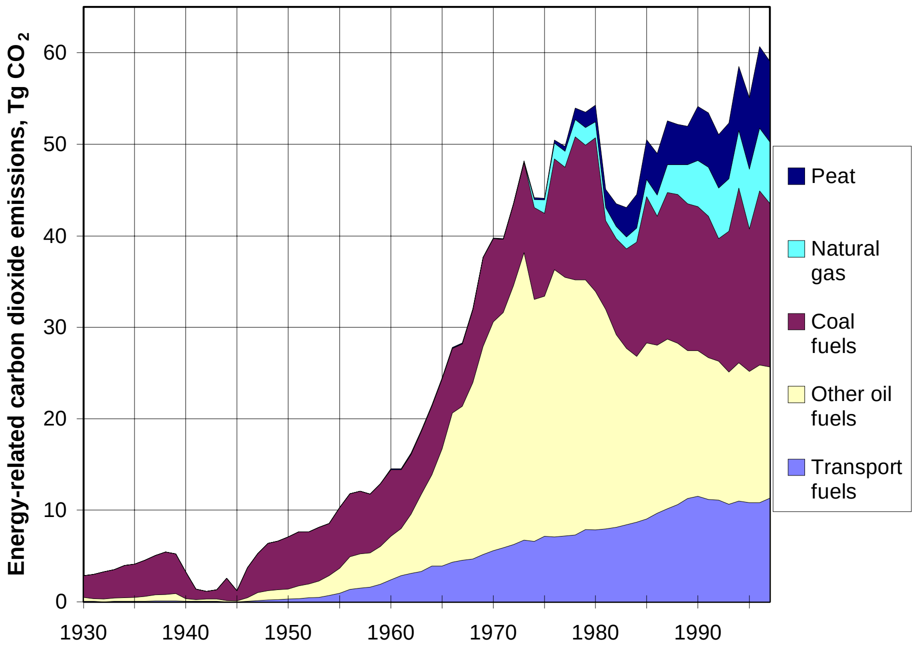

Figure 3. Finnish carbon dioxide emissions from fossil fuels and peat between 1930 and 1997 (Statistics Finland 1997a, Salonen 1981).

A more detailed emission inventory is shown in Table 2 for the years 1990 and 1995. The total carbon dioxide emissions were about 54 Tg in 1990 and about 55 Tg in 1995. There is a small difference between the 1990 inventory shown in this table and the updated official inventory shown in Table above. The difference is mainly due to variations in the amounts of peat and refinery gases combusted, for which the official inventories are as yet unpublished.

Table 2. Summary of the carbon dioxide emissions from combustible fuels in Finland in 1990 and 1995. Fractions of carbon not oxidised (based mainly on IPCC, 1997) have been taken into account in the emission factors.

	Fuel energy, PJ[1]		**Em. factor**	**Emissions, Tg CO_2**		
Fuel or energy form	**1990**	**1995**	**t CO_2 / TJ**	**1990**	**1995**	**Notes**
Coke-oven gas	4.06	7.66	46.7	0.19	0.36	(2)
Coke, blast furnace	29.19	27.85	105.0	3.06	2.92	(2)
Coke, other	7.76	5.02	106.0	0.82	0.53	(3)
Steam coal	126.19	127.04	92.7	11.70	11.78	(3)
Peat	55.88	74.32	104.9	5.86	7.80	(4)
Heavy fuel oil	76.22	62.66	76.6	5.84	4.80	(3)
Gasoil/diesel	172.59	160.77	73.4	12.67	11.80	(3)
Gasoline	85.73	81.87	72.3	6.20	5.92	(5)
LPG	6.66	7.11	62.7	0.42	0.45	(3)
Jet kerosene	5.52	4.87	70.8	0.39	0.35	(3)
Other kerosene	0.12	0.21	71.0	0.01	0.02	(3)
Other oils	0.12	0.12	72.6	0.01	0.01	(3)
Petroleum coke	2.39	1.49	98.8	0.24	0.15	(3)
Refinery gas	7.59	4.26	58.7	0.45	0.25	(4)
Refineries' own use	20.83	23.31	61.3	1.28	1.43	(6)
Natural gas	90.76	117.18	55.8	5.06	6.54	(3)
Biomass & waste	158.64	208.27	0.0	0.00	0.00	(3)
Nuclear	197.76	197.76	0.0	0.00	0.00	
Hydro & wind	38.70	46.08	0.0	0.00	0.00	
Electr. imports	38.67	30.26	0.0	0.00	0.00	
Reaction heat	7.14	6.51	0.0	0.00	0.00	
Total primary energy	**1132.52**	**1194.64**		**54.2**	**55.1**	

[1] Source for energy data is Statistics Finland (1997a), except for coke-oven gas (IEA 1998).

[2] The emission factor for coke-oven gas is based on national evaluation, but close to that proposed by IPCC. The emission factor for blast-furnace coke assumes a fraction of 3% stored or unoxidized.

[3] Reference for emission factor: IPCC (1997).

[4] Reference for emission factor: Boström (1994).

[5] Emission factor is based on Sweden (1997), as the factor in the IPCC Refence Approach (69 t / TJ) appears to be too low, and the IPCC data for European gasoline cars appear to bee somewhat high.

[6] Boström (1994) assumes the same emission factor for refineries' own use as for residual fuel oil. However, about 85% of the own use consists of refinery gases and natural gas, the rest being mainly heavy oil. Therefore, an average emission factor equal to that of ethane is estimated as appropriate.

The calculation of carbon dioxide emissions from fuel combustion is straightforward for most fuels categories. The gross emission factors (based on lower heating values) and coefficients of unoxidised fractions (IPCC 1997) are simply applied to the amounts of lower heating values of the fuels. A few complications arise with the use of coking coal and its derivatives, and with refineries' own use. Coking coal is a primary fuel used exclusively for the production of coke. As stated in the IPCC guidelines, it is not necessary to calculate the emissions based on the use of coking coal, provided that all the carbon flows leaving the transformation process are covered elsewhere. Therefore, the emissions can be calculated from the use of coke, coke-oven gas, and coking tars. The production of coke-oven gas is not given in publicly available Finnish national statistics, but is reported in the IEA Basic Energy Statistics (IEA 1998). The IEA figures for coke-oven gas have been used for the summary in Table 2.

When estimating the emissions from the combustion of reducing agents in blast furnaces (mainly coke) IPCC recommends using the formula

$$\text{Emission (tonnes } CO_2) = M_{RA} \times EF_{RA} + (C_{Ore} - C_{Metal}) \times 3.67 \qquad (1)$$

where M_{RA} is the mass of the reducing agent, EF_{RA} is the emission factor in tonnes CO_2 per mass unit, while C_{Ore} and C_{Metal} are the masses of the carbon in the iron-ore and in the steel, respectively. The amount of carbon in the ore can be estimated to be negligible in Finland. The carbon content of the steel is assumed to be less than 0.5%, and the amount of coke used is about 420 kg / tonne steel. As the emission factor is 3.13 tonnes CO_2 per tonne coke, the fraction of carbon stored in the steel can be calculated to be at most 1.5% of the carbon content of the coke. Taking into account that some additional carbon residues will remain in the slag, the total fraction of carbon unoxidised may be estimated to be around 3%. This is the fraction applied to the coke combusted in blast furnaces.

The carbon dioxide emissions from refineries' own use have been estimated using the information available about the actual fuel mix. Refinery gas is by far the most important fuel, but residual waste oils constitute another significant component. Therefore, the average emission factor has been estimated to correspond approximately to the emission factor of ethane, which is the basis of the emission estimate in Table 2.

2.2.3 Industrial processes

Some industrial processes oxidise fuels basically as feedstock. The reduction of iron in a blast furnace through the combustion of coke is a good and classic example. According to the IPCC guidelines, the emissions should in such cases be considered to be industrial, as the primary and direct purpose of the fuel combustion is to produce pig iron, not energy. In the present study, however, CO_2 emissions are divided according to the type of the CO_2 releasing process (fuel combustion vs. other types of oxidisation). Carbon dioxide emissions from industrial processes are therefore in this study defined to include emissions from other than fuel combustion activities only. The emissions from the use of fuels as reducing agents in basic metals manufacturing and non-metallic minerals production are included as emissions from fuel combustion activities.

Process emissions of carbon dioxide in Finland are produced primarily from various uses of limestone. In processes where limestone is heated at high temperatures, calcium carbonate ($CaCO_3$) is transformed into lime (CaO) and carbon dioxide. Assuming that this calcination reaction is complete, 0.44 kg of CO_2 is released for each kg of limestone used. Another important source is the use of soda ash (natrium carbonate) e.g. in the manufacturing of glass, metals and pulp. For each kg of soda ash used, 0.412 kg CO_2 is released (IPCC 1997). Historically, also the manufacturing of ammonia has produced considerable emissions, but due to diminished production volumes the emissions are very small at present. Table 3 gives summary estimates for the industrial process emissions in 1990 and 1995. The estimates differ slightly from the official inventories because of different approaches to limestone use in the iron and steel industry.

Cement and lime manufacturing are important utilisers of the calcination process. However, a similar process occurs also in many other industrial applications of limestone. In integrated steel manufacturing, limestone (or burnt lime) flux is added to the blast furnace and the basic oxygen furnace, typically at a total rate of about 250 kg limestone equivalent per tonne iron produced (IPCC 1997). In Finland the rate is somewhat lower, and is estimated to be about 230 kg [1]. The limestone flux is calcinated during the process and gives

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[1] Estimated on the basis of the information on limestone use given in the Raahe steel works environmental statement 1996 (http://www.rautaruukki.fi/environ//env.htm).

off carbon dioxide. In the manufacturing of kraft pulp a recycling causticizing process is involved in the recovery of pulping chemicals. Limestone is burnt into lime in the process, but only a small part of the carbon is from limestone added to the process to compensate for losses in calcium. Relatively large quantities of limestone are also used for flue gas desulphurisation, where limestone is burnt into lime in order to bind the sulphur dioxide into gypsum. The estimates for pulp manufacturing and desulphurisation in Table 3 are mainly based on the approaches used by Boström et al. (1992). Production figures are mainly from Statistics Finland (1998a, 1993), and soda ash consumption is based on Board of Customs (1997).

Table 3. Summary of estimates for the carbon dioxide emissions from industrial processes in Finland in 1990 and 1995.

Year	**1990**	**1995**	**1990**	**1995**
Product	Production, Gg		Use of limestone to be burnt, kg per kg product	
Cement	1650	907	1.20	1.16
Pig iron	2283	2242	0.23	0.23
Chemical pulp	4870	5782	0.003	0.003
Desulphurised SO_2	5	31	1.88	1.88
Burnt lime (other)	274	282	1.78	1.78
	Calcinated limestone, Gg		CO_2 emissions, Tg	
Cement	1973	1052	0.87	0.46
Pig iron [1]	525	516	0.22	0.22
Chemical pulp	15	17	0.006	0.008
Desulphurised SO_2 [2]	9	58	0.004	0.026
Burnt lime (other) [1]	464	478	0.20	0.21
Total	2951	2121	1.30	0.92
	Use of soda ash, Gg		CO_2 emissions, Tg	
Soda ash use	55.7	61.4	0.02	0.03
Total CO_2 from industrial processes, Tg			**1.32**	**0.95**

[1] Assuming a calcination ratio of 95%.

[2] 60% of the total SO_2 desulphurisation in coal boilers (51.6 Gg SO_2) assumed to be limestone-based in 1995. 20% excess calcination of limestone assumed.

2.2.4 Fugitive emissions

Fugitive carbon dioxide emissions are produced during fuel acquisition, refining, transport, and storage. In Finland, fugitive carbon dioxide emissions arise particularly from peat production. The emissions are due to peatland preparation, and profiling, and stockpiling of harvested peat. According to the results from life-cycle analyses of peat production and utilisation, the proportion of the fugitive emissions to emissions from the combustion phase are in the range of 5–15% (Mälkki & Frilander 1997). Additionally, some 150 000 ha of cultivated peatland are classified as reservoirs for future peat production. The specific CO_2 emissions from such peatlands have been estimated to be about 350 g C $m^{-2}a^{-1}$ (Savolainen et al. 1994). The official Finnish estimate for the year 1990 is 1 Tg (CO_2) for the production phase and 2.5 Tg (CO_2) for the reservoirs, which correspond to conservative estimates of 17% for the production in proportion to combustion emissions, and 450 g C $m^{-2}a^{-1}$ for the peatland reservoirs. Using the same specific emissions, the total emissions in 1995 can be calculated as about 4.0 Tg CO_2.

Apart from the peat fuel cycle, some fugitive emissions can arise also from domestic transportation and storage of coal (coal is not produced in Finland). The emissions from domestic transportation are estimated to be very small. Long-term reserve stockpiles of coal amount to about 3.5 Tg coal (MTI 1996). Operational stockpiles correspond typically to about three months' consumption. Consequently, the total amount of coal in stockpiles is at present about 5 Tg.

In most estimates for coal-fired power or heat plants the annual losses in the heating value of stored coal are estimated to be 2% (e.g. Kosunen & Leino 1995). In practice, in reserve stores with long turnover times and careful storage methods the losses can be smaller. As the annual dust emissions from the stockpiles correspond to less than 0.1% of coal in the stockpiles (Lemettinen et al. 1996), most of the losses must be caused either by oxidisation or by the release of volatile organic compounds from the coal (e.g. methane). Assuming that the loss is exclusively caused by oxidisation, the annual amount of carbon dioxide emissions corresponding to a 2% loss would be about 0.24 Tg (CO_2). If, however, a significant part of the losses were caused by volatile compounds emitted, considerable methane emissions could also be involved. Nevertheless, as yet the emissions from coal stockpiles have not been estimated in the national inventories.

2.2.5 Non-energy use of fuels

The use of many products containing carbon from non-energy uses of fuels produce carbon dioxide emissions at various oxidisation rates. Such emissions arise from, for example, the oxidisation of lubricants in transportation and the oxidisation of many chemical products at various stages of their life-cycles. Such an oxidisation occurs most definitively in the incineration of waste containing e.g. plastics and other fossil-fuel based products. Detailed figures about the emissions involved have not been published in Finland. A crude assessment can be obtained by applying the estimates for the fractions of carbon stored in products in the IPCC reference approach. A summary calculation for the years 1990 and 1995 is presented in Table 4. According to this crude estimate, the total amount of carbon dioxide emissions would be about 0.7 Tg for both 1990 and 1995. The official estimate for 1990 is 0.6 Tg, as presented in Table 1 above.

2.2.6 Land-use

Deforestation, afforestation or changes in the biomass stocks are not considered in the present study. Fossil carbon dioxide emissions related to land-use may be produced from limestone and dolomite which are commonly used for soil amelioration. When added to acid soil these minerals release CO_2 in the bicarbonate equilibrium reaction. In most instances where liming is practised, repeated applications are made every few years. Therefore, one can assume that the addition rate of lime is in near equilibrium to the consumption of lime

Table 4. Summary of carbon dioxide emissions from non-energy uses of fuels in Finland in 1990 and 1995.

Fuel form	**Unit**	**Energy TJ / unit**	**CO_2 factor Mg / TJ**	**Fraction of C stored** [1]	**Amounts used** [2] **1990**	**1995**	**CO_2 emissions, Gg 1990**	**1995**
Lubricants	Gg	40.2	73.3	50%	118	103	174	152
Naphta feedstock	Gg	44.4	73.3	75%	375	344	305	280
Gasoil feedstock	Gg	42.5	77.4	50%	34	35	56	58
Natural gas feedst.	Mm3	36.0	56.1	33%	28	37	38	50
LPG feedstock	Gg	46.3	63.1	80%	81	68	47	40
Refinery gas feedst.	Gg	51.9	66.7	80%	53	50	37	35
Coking tars	Gg	28.0	94.6	75%	38	71	25	47
Total					**581**	**568**	**682**	**661**

[1] Fractions of carbon stored according to IPCC Reference Approach (IPCC 1997).

[2] Fuel amounts taken from Statistics Finland (1997a), and for coking tars from IISI (1996).

applied in previous years. Emissions associated with the use of carbonate limes can thus be calculated from the amount and composition of the lime applied annually within a country (IPCC 1997).

According to statistics (Statistics Finland 1993, 1998a), the amounts of domestic limestone and dolomite used for soil conditioning in 1990 were 569 Gg and 714 Gg, respectively. In 1995 the corresponding amounts were 583 and 204 Gg. Information on the possible use of imported limestone for soil liming has not been available, but such imports can be estimated to be small. Using the amounts given above and the approach suggested by IPCC, carbon dioxide emissions from the liming of soils were about 0.6 Tg in 1990, and about 0.4 Tg in 1995.

2.3 Methane

2.3.1 Overview

Methane (CH_4) is reactive and more effective greenhouse gas than carbon dioxide. The average lifetime in the atmosphere is very short compared to other greenhouse gases — about 9–15 years. The most significant removal process for methane is in reaction with hydroxyl radical (OH). Addition of methane to the atmosphere reduces the concentration of tropospheric OH, which can in turn feed back and reduce the rate of methane removal. The concentration of methane in the atmosphere has been growing due to human activities: in the pre-industrial era it was about 0.7 ppm_v and nowadays is about 1.7 ppm_v (IPCC 1996a).

Methane emissions arise mostly from organic matter which is degraded anaerobically by microbial activities. In nature this kind of activity occurs mostly in wetlands, which are the most significant natural methane emission source. In Finland natural methane emissions originate from mires and water systems. (Pipatti 1997) The amount of the methane emission from mires depends on the wetness of the mire, and therefore ditching might decrease the CH_4 emissions (Laine et al. 1996). Methane emissions from water systems originate from anaerobic microbiological processes in the sediment layer (Forsius et al. 1996, p. 189).

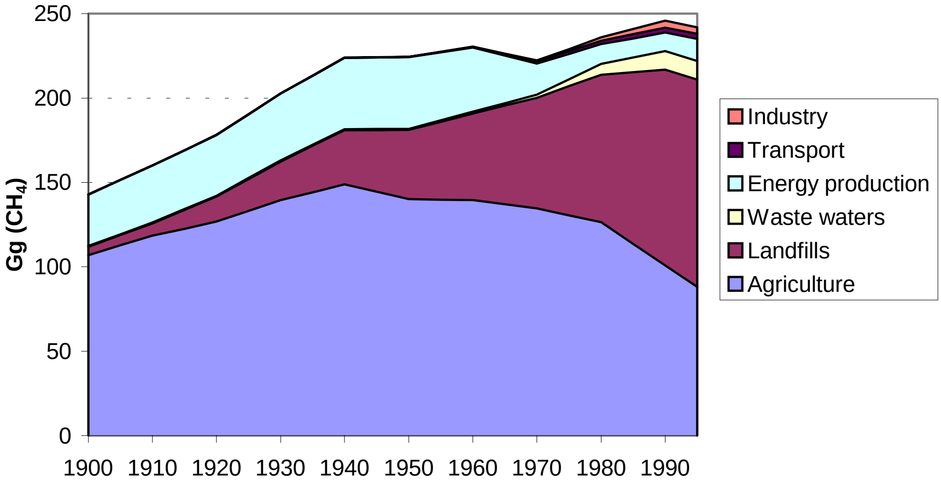

Figure 4. Finnish methane emissions between 1990–1995 (Forsius et al. 1996, p. 193).

In Finland anthropogenic methane emissions correspond to approximately a half per mille of global anthropogenic methane emission (Pipatti 1997). Emissions are due to waste management, animal husbandry, burning processes, and industrial processes. On a global scale, fossil fuel production and rice cultivation are also important methane emission sources. Finnish anthropogenic methane emissions from 1900 to 1995 are presented by source in Figure 4, from which it can be seen that the emissions from agriculture and from energy production have been decreasing, which is due to the decreases in the amounts of cattle and small-scale burning of biomass. It should be noticed that the CH_4 emissions in Figure 4 do not match with emission estimates made in the present study, because the methods of calculation have been changed.

2.3.2 Waste management

The most significant anthropogenic methane emission source in Finland is waste management, which was the cause of about 60 per cent of anthropogenic methane emissions in 1995. Most of those emissions originate from landfills. Waste water treatment is also known as a methane source, but emission estimates are so inaccurate and the amounts so insignificant, that these are not taken into consideration in this study. Methane from waste water treatment arises only from anaerobic treatment, which occurs in only about 5 per cent of waste water treatment in Finland (Pipatti et al. 1996, p. 59). Also, in many cases, the methane is recovered.

Landfill gas emissions are due to the organic fraction of waste, which degrades anaerobically in waste layers. Landfill gas contains roughly 50 per cent methane and 50 per cent carbon dioxide. The amount of formed methane depends on the amount of degradable organic carbon (DOC) in waste, on the thickness of waste layers, and on temperature. Significant types of waste involving methane emissions are municipal solid waste (MSW), industrial solid waste, construction and demolition waste, municipal sludge, and industrial sludge. (Pipatti 1997, Pipatti et al. 1996)

The amount of DOC in waste depends on the composition of waste, because every fraction of waste has a specific DOC-content. In Finland there is no official or exact knowledge of the composition, and therefore the data used are based on estimates. In this study the estimation is based on data from Tanskanen (1996). The DOC content data have been taken from the estimates of Bingemer and Crutzen (1987) and Pipatti (et al. 1996). The data are presented in Table 6.

The data in Table 5 are based on the wet weight of waste. Plastic contains roughly 50 per cent carbon, but it is not organically degradable. The DOC content of other combustible waste has been estimated by assuming that it contains 50 per cent plastic and 50 per cent paper and board; and therefore the DOC content is 20 per cent. The DOC contents of other sorts of waste are presented in

Table 5. The composition of MSW and the DOC-content of different fractions of MSW.

Fraction	**Share (weight per cent)**	**Average DOC-content (weight per cent)**
Paper and board	27	40
Organic waste	33	16
Glass	5	0
Metal	5	0
Plastic	7	0
Textiles	2	40
Other combustible	16	20
Other non-combustible	5	10

Table 6. The DOC-contents of other sorts of landfilled waste.

Sort of waste	**DOC-content (weight per cent)**
Industrial solid waste	7
Dried industrial sludge	10
Liquid industrial sludge	1–2.5
Dried municipal sludge	10
Liquid municipal sludge	1–2.5
Construction and demolition waste	18

In Table 6 the DOC content of industrial solid waste has been roughly estimated from its composition (Pipatti et al. 1996). The content of dry matter in sludges is about 2–5 weight per cent in liquid sludge and about 20 weight per cent in dried sludge[1]. About 50 per cent of dry matter is degradable organic carbon. The estimate for DOC content of construction and demolition waste has been calculated with help of data presented by Tanskanen (1996, p. 29).

The calculation of methane emissions from landfills is usually done in two different ways: with the mass balance model and with a kinetic approach (IPCC 1997). In this study the mass balance model is used because the forthcoming national greenhouse gas inventories are based on that approach. Consequently, historical data on the amounts of landfill waste, which would have caused some uncertainties in results, are not needed. The modelling of landfill gas recovery will also be quite straightforward with the mass balance approach.

The weakness of the mass balance model is that it does not take into account that methane is emitted from landfill waste over a long time period, rather than instantaneously. It is assumed that the total methane production potential will be emitted during the same year as the waste is disposed of. The model will give a reasonable estimate, if the amount of landfill waste is quite stable over the study period (Pipatti et al. 1996).

According to the mass balance model the annual methane emissions for different sorts of waste can be calculated with help of Equation 2.

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[1] Personal communication with Tuula Rytkönen, Finnish Environment Institute, The Pollution Prevention Division.

where

MCF	is the methane correction factor which depends on the type of landfill
DOC_F	is the portion of carbon in DOC converted to landfill gas (≈ 50 per cent)
F_{CH4}	is the fraction of methane in landfill gas (≈ 0.5 g(CH_4-C)/g gas-C)
CF_0	is the mass correction factor (= 16 g(CH_4)/12 g(C))
OX	is the oxidation factor
M_{waste}	is annual amount of landfill waste. (IPCC 1997)

The values of the methane correction factor *(MCF)* in different types of disposal sites are presented in Table 7.

MCF is not a well known quantity, and therefore many uncertainties exist. In managed landfills there is controlled placement of waste. Cover material, mechanical compacting or levelling of waste are also used. According to the new waste law the landfill waste must be compacted and covered (The Finnish Council of State 1997), and so it is assumed that all disposal sites can be considered as managed in the near future. Due to these regulations, waste disposal will be centralised in large disposal sites, which are, in every case, managed. Therefore unmanaged small disposal sites will be closed.

With help from the values in Table 5, the average DOC content of Finnish MSW can be estimated, and the result is about 20 per cent. The fraction of carbon which is converted to landfill gas *(DOC_F)* depends mainly on the temperature in the waste layers. It has been estimated that in Finnish meteorological conditions the value of DOC_F would be about 50 per cent of weight. Remaining carbon will be stored in disposal sites (Pipatti et al. 1996).

Table 7. The effect of type of disposal site to methane emissions (IPCC 1997).

Type of disposal site	MCF
Managed	1
Unmanaged (>5m waste)	0.8
Unmanaged (<5m waste)	0.4
Uncategorised	0.6

The oxidation of methane in the surface layers of the landfills is also significant quantity, because it directly affects the amount of emitted methane. According to IPCC (1996b) it can be assumed that 10 per cent of methane is oxidised. By inserting the values referred to above in equation (2), the emission factor for methane emissions from landfill MSW can be calculated. The result is 60 kg (CH_4)/Mg (wet waste) or 300 kg (CH_4)/Mg (DOC). The latter value is used in the model-based calculations to estimate the emissions.

The oxidation factor is not taken into account in the calculation of the amount of the recoverable landfill gas in waste layers. In that case the factor is about 185 m^3 (landfill gas)/Mg (wet waste)[1]. This figure seems to be reasonable, when compared with a Swedish study, in which it has been estimated that about 200 m^3 (landfill gas)/Mg (wet waste) is formed in waste layers (SNV 1993, p. 14).

2.3.3 Agriculture

The contribution of agricultural methane emissions in Finland to the total anthropogenic CH_4 emissions is also of importance – about 30–40 per cent in 1995. The emissions are mostly due to enteric fermentation of animals, and manure management. The emission calculation methods are based on IPCC (1997).

The emissions from enteric fermentation are dependent primarily on the type of digestive system and the feed intake. Ruminant animals have the highest emissions because a significant amount of digestion occurs within the rumen in methane-producing fermentation conditions. (IPCC 1997) In Finland the ruminant animals are cattle and sheep. However, the contribution from sheep is very small. About 95 per cent of the CH_4 emissions from enteric fermentation are due to cattle, and therefore the calculation of the emission factors has been done with a more detailed approach. For other animals default emission factors are used.

In the emission estimation for enteric fermentation of cattle many country-specific details are taken in account: the consumption of feed energy in

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[1] The specific weight of methane in 25 degrees of Celsius is about 0.72 kg/m^3.

maintenance of energy equilibrium, in grazing, in milk production, in weight gain, and in pregnancy. The input data for emission estimation should contain estimates for feed digestibility, the length of the grazing period, average daily feed intake, weight, average weight gain, milk production, and the number of nascent calves. (IPCC 1997)

The input data used in this study is primarily based on Pipatti (1997, p. 17) and IPCC (1997). The scenario estimate for milk production of dairy cattle is taken from The Ministry of Environment (1997, p. 21), in which it has been assumed that milk production per animal will increase in the future. The emission factor for other cattle has been calculated as number-weighted mean value from the specific emission factors of bulls, heifers, calves and nursing cattle. The milk production of nursing cattle has been estimated to be constant in the future.

The methane emissions from manure management have also been calculated using the methods of IPCC (1997) and with the initial data used in Pipatti (1997). The emissions also depend in this case on many factors, such as: the amount and the sort of manure, the management system and the climate. The amount and the sort of manure are dependent on animal category, the size of animal and feeding. In Finland the manure is managed as liquid or solid manure. The emissions are multiple in liquid manure management compared with solid manure management. The grazing period, when manure is left on the ground, is also taken into account in the method of calculation.

The calculated emission factors for enteric fermentation and for manure management are presented in Table 8. When the emissions from manure management are calculated, estimates of the proportions of the manure management which are liquid or solid are also necessary. The estimates in this study are based on a survey which has been made for the study of agricultural ammonia emissions in Europe (Pipatti 1997, p. 19). According to the survey, 20 per cent of dairy cattle, 60 per cent of other cattle, and 70 per cent of swine are within liquid manure management. The manure of other animal categories is managed only with solid methods. It has been assumed that the share of liquid manure management will increase 10 percentage units by 2025.

Table 8. The calculated agricultural methane emission factors (kg(CH_4)/animal/a).

Animal category	**Enteric fermentation**	**Liquid manure management**	**Solid manure management**
Dairy cattle [1]	97	15.2	2.2
Other cattle	47	5.2	0.7
Swine	2	5.6	0.6
Sheep	8	-	0.2
Horses	18	-	1.4
Poultry	-	-	0.1

2.3.4 Energy

The contribution of the energy sector to the total CH_4 emissions is less than 10 per cent in Finland. In combustion processes methane is emitted when fuel does not burn completely. About 50 per cent of methane emissions from energy production are due to small-scale combustion of biomass (mainly firewood), although its share of primary energy consumption is below 3 per cent (Pipatti 1997, p. 13). Another significant emission source is transportation. In power plants the CH_4 emissions are relatively small, because the combustion is more complete than in small-scale burning and in motors. The emissions from combustion processes are estimated with emission factors (Appendix A) based on ILMARI-model, which is in use in Statistics Finland (Statistics Finland 1997b).

Methane is also emitted from the natural gas grid. In Finland emissions occur mostly during the extension and maintenance of the grid. In 1995 the CH_4 emissions due to above operations were about 0.2 Gg[2]. Leakage emissions are insignificant because the grid is quite new and can be effectively maintained.

In the fuel supply sector methane is emitted in coke production. According to the IPCC inventory manual (IPCC 1997, Chapter: Industrial Processes), coke production causes 0.5 kg(CH_4) per ton of coke. This value can be converted to

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[1] The emission factor has been calculated as an example by choosing the 1995 milk production level. In model-based calculations a scenario for milk production is used when emission factors are calculated.

[2] Personal communication with Kari Grönfors, Statistics Finland.

emissions per energy unit with help of the lower heating value of coke (28.1 MJ/kg). In this case the emission factor is 0.018 g(CH_4)/MJ. In the earlier IPCC inventory manual methane emissions from coke production have been reported under industrial methane emissions, which also included emissions from the manufacturing of iron. In the more recent IPCC manual these emissions are not mentioned. Therefore coke production is the only industrial source, which has been taken into account in this study.

2.3.5 Other anthropogenic sources

It has been noticed that man-made lakes can cause considerable methane emissions. This is due to anaerobic degradation of vegetation, which remains under the surface of water. According to the measurements, the CH_4 emissions from man-made lakes might be a considerable addition to anthropogenic methane emissions in Finland (Forsius et al. 1996, p. 189). Knowledge of these emissions is so inaccurate that they are not considered in this study.

2.4 Nitrous oxide emissions

2.4.1 Overview

Nitrous oxide (N_2O) is a long-lived and very effective greenhouse gas. Its lifetime in the atmosphere is about 120 years and it is mainly removed from the atmosphere by degradation caused by solar radiation. The concentration of nitrous oxide in the atmosphere has increased about 15 per cent since the pre-industrial era due to human activities. Most of the anthropogenic N_2O emissions are due to agriculture and industrial processes. Levels of natural N_2O emissions are not well known but they are estimated to be twice as high as anthropogenic emissions. (IPCC 1996a, p. 19) In Finland natural N_2O emissions are probably caused by forests and mires. It has been estimated that from these sources about 4.5 Gg(N_2O)/a is emitted (Forsius et al. 1996, p. 192). This estimate includes, however, some anthropogenic effects, such as nitrogen deposition and ditching of mires. In general, it is difficult to differentiate between natural and anthropogenic N_2O emissions.

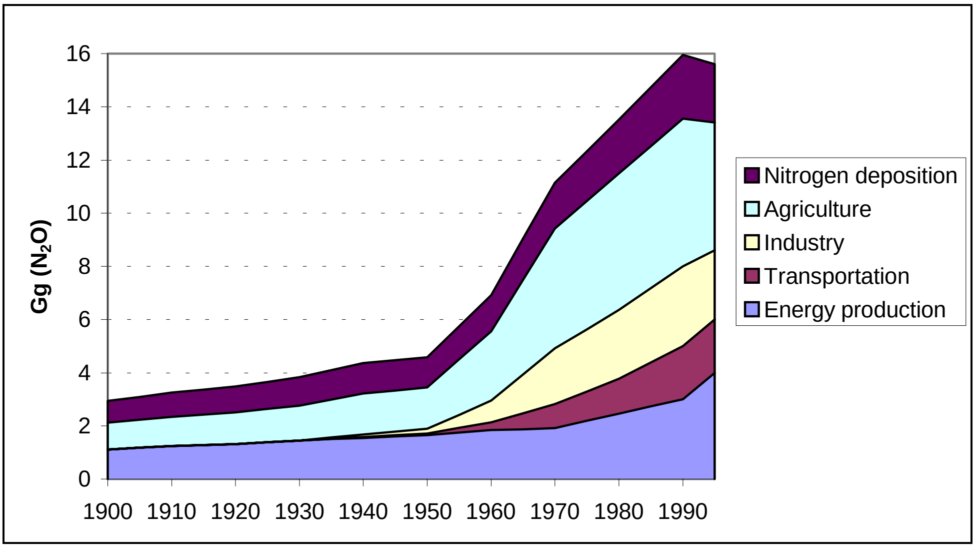

Figure 5. The development of Finnish N_2O emissions between 1990–95 (Forsius et al. 1996, p. 193).

In Finland anthropogenic N_2O emissions are due to energy production, agriculture, transportation, manufacturing of nitric acid, and atmospheric nitrogen deposition (Pipatti 1997). The significance of these emission sources is presented in Figure 5. The emissions from peatlands are not included in the Figure (see Section 2.4.3).

2.4.2 Energy

The contribution of the energy sector to the total anthropogenic N_2O emission is about 35 per cent in Finland (The Ministry of Environment 1997, p. 22). About 75 per cent of these emissions are due to energy production and the rest is due to transportation. In energy production the fluidised bed combustion (FBC) has high specific emissions compared with other burning techniques, and it causes a relatively large proportion of the N_2O emissions from the energy sector in Finland. However, it is, in many respects, an environmentally friendly technology, as it allows the burning of relatively low-grade fuels with high efficiency and low emissions. High N_2O emissions in FBC are due to a relatively low combustion temperature, which contributes to the formation of N_2O. The most significant formation process of N_2O is the oxidation of fugitive cyano and cyanide compounds of fuel. For example the reaction of hydrogen cyanide to N_2O is the following (Kilpinen 1995):

$$\begin{aligned} HCN + O &\rightarrow NCO + H \\ NCO + NO &\rightarrow N_2O + CO \end{aligned}$$

A comparable situation to the FBC in energy production occurs in the transport sector. The catalytic converters in cars decrease the emissions of NO_x, VOC and CO to a large extent, but they increase the emission of N_2O. In catalytic converters nitrogen oxides (NO_x) formed in combustion are reduced to N_2O (Pipatti 1997). The N_2O emission factors used in calculations for energy production and transportation are presented in Appendix A.

Burning processes also cause indirect N_2O emissions because a part of the atmospheric deposition of nitrogen, which is due to emissions of nitrogen oxides (NO_x), converts in the soil into N_2O. This is considered in more detail in Section 2.4.5.

2.4.3 Agriculture

The most important source of agricultural N_2O emission is the nitrogen load of soil, which is mostly due to the use of synthetic fertilisers. The nitrogen load increases natural nitrification and denitrification processes, in which nitrous oxide is emitted to the atmosphere. Animal manure and crop residues in the fields also increase nitrogen load. Cultivation of legumes and application of sludge are also known as N_2O emission sources, but their significance is small and emission estimates are uncertain. Unfertilised peatlands has been noticed to emit N_2O more than natural soil, but these emissions are also not well-known. (Forsius et al. 1996)

It has been estimated that 1.25 per cent of nitrogen in the soil is emitted to the atmosphere as N_2O. A small part of the nitrogen is also emitted in gaseous form, mostly as ammonia (NH_3), which must be subtracted before calculation of direct N_2O emissions. (IPCC 1997) It has been estimated that in Finland this share is on the average 0.75 per cent for synthetic fertilisers (Grönroos et al. 1998) and about 30 per cent for animal manure. Consequently, the N_2O emission factor for synthetic fertilisers is about 19.5 kg (N_2O) per ton of nitrogen applied to the fields. The ammonia emissions from the same source are about 9.1 kg (NH_3)/t

Table 9. N_2O and NH_3 emission factors for the different animal categories.

Animal category	**N_2O emissions kg(N_2O)/ animal/a**	**NH_3 emissions kg(NH_3)/ animal/a**
Dairy cattle	1.26	31.50
Other cattle	0.50	12.20
Swine	0.11	3.49
Sheep	0.23	4.20
Horses	0.84	17.60
Poultry	0.01	0.34

(N). The calculation of ammonia emissions is necessary, because they cause indirect N_2O emissions. This is considered in Section 2.4.5.

The N_2O and NH_3 emissions from animal manure applied to the fields must be calculated for each animal category, because the amount of nitrogen excreted varies between the different animals. The amounts of nitrogen excreted by animals are based on Grönroos (et al. 1998) and they have been adjusted for the animal categories used. Volatilisation of NH_3 from manure occur in many phases of manure management, which have been taken into account in the calculation of N_2O emission factors. Ammonia emissions factors have been taken directly from Grönroos (et al. 1998). The N_2O and NH_3 emission factors used for the different animal categories are presented in Table 9.

The nitrogen, which returns to the soil from the crop residues left on the fields, increases nitrogen load. In the calculation of N_2O emissions the factors needed are the amount of residues left on the fields and the amount of nitrogen in residues. It has been estimated that the total amount of straws is the amount of crop production multiplied by 1.35 and that straw contains 0.5 per cent of weight as nitrogen[1]. The N_2O emission factor based on these values is 63 g (N_2O) per ton of crop produced. In this case the method of calculation of IPCC (1997) has been found to lead an overestimate.

The cultivation in peatlands has been estimated to cause about 4 Gg (N_2O)/a in Finland (The Ministry of Environment 1997). Arable lands, in which the

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[1] Personal communication with Riitta Pipatti, VTT Energy.

concentration of organic matter is over 40 per cent, are categorised as peatlands. In Finland there are about 200,000 hectares of these kind of fields in cultivation (Laine et al. 1996, p. 121). According to the most recent IPCC inventory methods, peatlands emit about 7.9 kg N_2O/ha/a, i.e. about 1.6 Gg (N_2O)/a, which is a considerably lower estimate than the earlier ones. However, the emissions and the area of peatlands are not well-known, and therefore the estimate is inaccurate.

2.4.4 Industrial processes

In Finland the only significant industrial source of nitrous oxide is the manufacturing of nitric acid (HNO_3). On a global scale, the manufacturing of adipic acid is also an important industrial source. The manufacturing of nitric acid takes place in two factories (in Siilinjärvi and in Uusikaupunki) with a single-phase middle pressure process. The Norwegian company Norsk Hydro has determined emission factors for different processes by taking measurements. For the middle pressure process the emissions are estimated to be 6–7.5 g (N_2O) per kg of produced HNO_3 (IPCC 1997). Consequently, the Finnish industrial N_2O emissions are nowadays about 3–4 Gg (N_2O).

2.4.5 Atmospheric nitrogen deposition

Nitrogen oxide (NO_x) and ammonia (NH_3) emissions are the cause of indirect N_2O emission, because about 1 per cent of nitrogen in these compounds converts into N_2O. According to IPCC inventory methods N_2O emission factors for NO_x and NH_3 emissions are about 4.8 g (N_2O)/kg (NO_x) and 12.9 g (N_2O)/kg (NH_3) respectively (IPCC 1997). NO_x emissions are mainly due to transportation and energy production. On the other hand, NH_3 emissions originate from agricultural activities, as mentioned in Section 2.4.3. The contribution of atmospheric nitrogen deposition to the total N_2O emission is nowadays about 10 per cent (Pipatti 1997). In practice, most nitrogen deposition in Finland is due to nitrogen emissions from other countries. Anyway, greenhouse gases will diffuse into the whole atmosphere, and therefore it is reasonable to associate the N_2O emissions from nitrogen deposition with the country from which the nitrogen emissions originate.

3. Calculation of the greenhouse effect

3.1 Additive concentrations of the greenhouse gases in the atmosphere

Greenhouse gases are removed from the atmosphere in various ways, and so additive concentrations of gases due to emissions decrease in the course of time. The kinetics of this kind of phenomenon can be described with the pulse response model, in which the removal rate of transient gas emission, in other words the pulse response, is assumed to be known. For example, the pulse response of a CO_2 emission can be described with equation 3.

$$f(t) = a_0 + a_1 e^{-\frac{t}{\tau_1}} + a_2 e^{-\frac{t}{\tau_2}} + a_3 e^{-\frac{t}{\tau_3}} + a_4 e^{-\frac{t}{\tau_4}} \qquad (3)$$

where the parameters a_i and τ_i has been estimated by fitting them in a model, which describes the circulation of carbon in the atmosphere-ocean system. It can be seen in equation 3 that according to the model, a part of the CO_2 emissions proportional to a_0 remains permanently in the atmosphere. The CO_2 uptake in oceans is a non-linear phenomenon: the greater the emission the larger the part of the emission will be that remains permanently in the atmosphere in the time-scale considered in the circulation model. In this case the value of the parameters (a_i and τ_i) depend on the amount of the initial emission, which has been used in their estimation (Korhonen et al. 1993). In this study, parameters, which are estimated with an initial emission that would increase the concentration of CO_2 in the atmosphere 25 per cent higher than in pre-industrial era, are used. This

Table 10. The parameters of the used pulse response model (Maier-Reimer & Hasselmann 1987).

i	a_i	τ_i (years)
0	0.131	
1	0.201	362.9
2	0.321	73.6
3	0.249	17.3
4	0.098	1.9

kind of concentration is close to the present level. The values of the parameters are presented in Table 10.

Methane and nitrous oxide have specific lifetimes in the atmosphere, and therefore the description of their pulse response is obtained from a single exponential function.

$$f(t) = e^{-\frac{t}{\tau}} \tag{4}$$

where τ is average lifetime of the gas. The lifetime of methane is on average 12 years and that of nitrous oxide is 120 years (IPCC 1997). In the calculation of the lifetime of methane, the decrease in the concentration of tropospheric OH due to an increase in CH_4 concentration has been taken into account (see Section 2.3.1).

The amounts of greenhouse gases in the atmosphere can be calculated by integrating the pulse response weighted emissions over the time period $t_0 \rightarrow t$.

$$x(t) = \int_{t_0}^{t} s(t-u) f(u) du + x_0 \tag{5}$$

where $x(t)$ is the amount of gas in the atmosphere at time t, $s(t)$ is the gas emission to the atmosphere, $f(t)$ describes the pulse response and x_0 is the amount of gas in the atmosphere at time t_0. (Korhonen et al. 1993)

The amounts of gas in the atmosphere, which can be calculated with equation 5, can be converted into concentrations with the help of the conversion factors in Table 11. The factors depend on the molecular weight of gases.

Table 11. Conversion factors (Houghton et al. 1997).

Gas	**ppb_v /Tg** [1]
CO_2	0.128
CH_4	0.353
N_2O	0.128

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[1] ppb_v = parts per billion by volume.

3.2 Radiative forcing

A common method for estimating the effects of the greenhouse gases is to calculate the radiative forcing, which is the perturbation to the energy balance of the Earth-atmosphere system. The radiative forcing due to emissions can be calculated, if the additive concentration in the atmosphere due to emissions is known. It is simply calculated by multiplying the additive concentration by the factors in Table 12, which have been calculated according to IPCC methods (Houghton et al. 1997).

Table 12. The conversion factors for the calculation of the radiative forcing.

Gas	**$mW/m^2/ppb$**
CO_2	0.0176
CH_4	0.4860
N_2O	3.7700

The radiative forcing due to additive concentration is also non-linear phenomenon, and therefore the conversion factors must be estimated by choosing some reasonable moment in time. The factors in Table 12 correspond to the situation in the year 1994. It has been assumed that the development of the radiative forcing per additive concentration will be constant in the future. This assumption is a slight overestimation, because in the case of the increasing

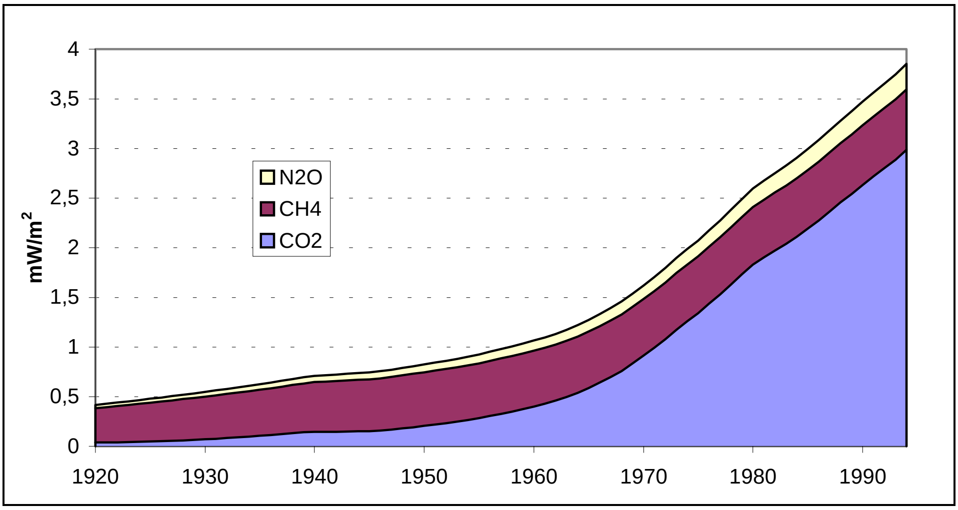

Figure 6. The radiative forcing due to Finnish CO_2, CH_4 and N_2O emissions between 1920 and 1994 (Korhonen and Savolainen 1998).

global average concentration, the absorption of infra-red radiation gets more saturated.

The development of radiative forcing due to Finnish greenhouse gas emissions (CO_2, CH_4 and N_2O) between 1920 and 1994 is presented in Figure 6. It can be seen that radiative forcing due to CH_4 emissions has been increasing very slowly. This originates from only small increases in emissions and from relatively fast removal compared to CO_2 and N_2O, whose radiative forcing values have increased strongly.

3.3 Global warming potential

Global warming potential (GWP) is one measure to compare the effect of alternative greenhouse gases. It is defined as the ratio of the integrated radiative forcing due to unit emission of a greenhouse gas to the corresponding value of CO_2. The values of GWPs can be calculated with equation (6).

$$GWP_i = \frac{\int_0^{t_f} \alpha_i c_i(t)dt}{\int_0^{t_f} \alpha_{CO_2} c_{CO_2}(t)dt} \qquad (6)$$

where α_i is the immediate increase in radiative forcing due to a unit change in the concentration of gas *i* (Table 12.), $c_i(t)$ is the concentration change at time *t* due to a unit of emission and t_f is integration time interval. The lifetimes of different gases vary, and so the GWP value depends on the integration time interval (Korhonen et al. 1993), as one can see in Table 13. The most common integration time interval in this case is 100 years.

Table 13. GWP values calculated with alternative integration times (IPCC 1996a, p. 22).

Gas	**20 years**	**100 years**	**500 years**
CO_2	1	1	1
CH_4	56	21	6.5
N_2O	280	310	170

4. Technical options for reducing greenhouse gas emissions

4.1 Abatement of carbon dioxide emissions

4.1.1 Energy supply sector

The total primary energy consumption has increased in Finland at an average annual rate of approximately 3.3% between 1950 and 1997. Thus, the growth in energy consumption has been almost as large as the economic growth. In many other countries the linkage between energy use and economic growth has been much weaker. One of the main reasons for this development in Finland is that an exceptionally high proportion of total energy is consumed within the industrial sectors, and the heavy industries have maintained their large contribution to the total industrial output. Another important factor has been the electrification of energy use in all sectors. This is illustrated by Figure 7, which shows the proportion of primary energy used for electricity supply out of the total primary energy consumption.

The increasing importance of the energy sector in the total energy supply emphasises its significance with respect to carbon dioxide abatement. However, energy supply technologies and infrastructure have inherently long lifetimes, which means that fundamental transitions in the supply sector may take decades. The options for carbon dioxide abatement in the energy sector can be grouped into the following categories:

- Improvements in conversion and distribution efficiencies
- Fuel switching to low-carbon or renewable fuels
- Switching to nuclear energy
- Switching to renewable non-combustion energy sources
- Recovery and disposal of CO_2 from flue gases.

It should be borne in mind that the abatement potentials of individual options are not additive, as the realisation of one option affects the potential of the remaining options, and several options may even be mutually exclusive. Therefore, a systems approach is needed in order to assess the realisable potential and impacts of combinations of individual measures. Estimates of the potentials and costs of the different measures are briefly discussed below. More detailed information on the actual description of the measures, and scenario assumptions are given in Sections 5.2 and 6.3.

Improvements in conversion and distribution efficiencies

Globally, the energy sector accounts for about 38% of the total carbon emissions from energy use (IPCC 1996c). The emissions are directly related to the losses in the conversion and transmission systems, particularly the losses in power generation. Within the OECD countries, the average conversion efficiency of combustible fuel-based power production is at present about 35 %. In Finland, the efficiency has long been considerably higher, as illustrated in Figure 7.

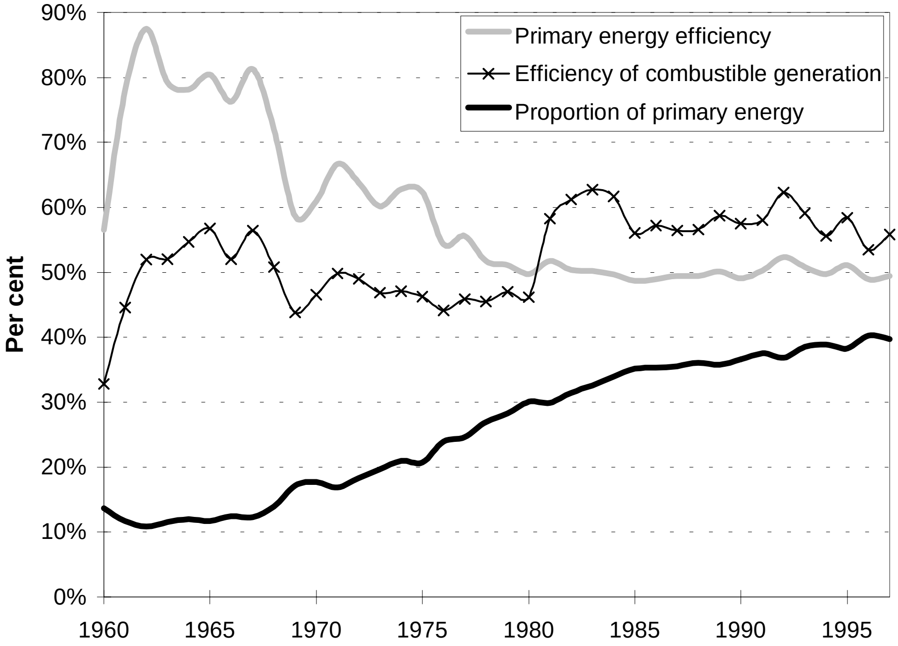

Figure 7. Average primary energy efficiency of the total electricity supply in Finland, average net efficiency of combustible fuel based generation, and the proportion of energy consumption of electricity supply to total primary energy consumption (Statistics Finland 1998b).

Table 14. Estimates for the costs and thermal efficiency (LHV) of some potentially important power and heat generation technologies.

Plant type	Plant size MW(e)	MW(h)	Investment FIM / kWe	Net energy efficiency	Year of commiss.	Reference Note
Separate power production						
Pulverized coal, conventional	500	0	4610	41.7%	~2002	1
Pulverized coal, conventional	1000	0	4610	41.0%	~2000	3
Pulverized coal, advanced	400	0	6220	49.5%	~2005	4
IGCC, coal	250	0	6700	48.0%	~2002	1
IGCC, biomass	60	0	6960	45.0%	~2005	5
IGCC, biomass	60	0	10280	45.1%	~2005	6
NGCC	300	0	3210	51.0%	~2002	1
NGCC	200	0	3160	50.0%	~2000	3
NGCC	200	0	3780	59.0%	~2005	4
Diesel engine, gas	100	0	3270	45.0%	~2002	2
Diesel engine, gas	40	0	4570	47.0%	~2005	4
Gas engine, biogas	1	0	4330	40.0%	~2005	4
District heat and power						
AFBC, coal	17	40	8100	86.3%	~2000	2
AFBC, biomass	17	40	8560	85.4%	~2000	2
AFBC, biomass	30	60	8310	85.5%	~1997	7
IGCC, coal	65	65	8270	85.0%	~2002	1
IGCC, biomass	65	65	8590	84.0%	~2002	1
IGCC, biomass	30	30	14200	90.0%	~2005	6
NGCC, gas	120	120	3690	84.0%	~2002	1
NGCC, gas	150	150	3700	89.0%	~2005	4
NGCC, gas	160	150	3970	90.0%	~1997	7
GT, WHB, gas	40	70	5210	85.5%	~2002	1
GT, WHB, gas	15	25	3300	91.0%	~2005	4
Diesel engine, gas	95	90	3740	87.0%	~2000	2
Diesel engine, gas	40	40	4730	93.0%	~2005	4
Gas engine, biogas	1	1.3	4570	91.0%	~2005	4
Fuel cell, MFCF	15	8	6300	90.0%	~2015	4
Fuel cell, SOFC	20	8	4730	90.0%	~2015	4

[1] Ekono 1997.
[2] Kosunen & Leino 1995.
[3] Unpublished cost estimates made at VTT Energy (Pirilä, P. & Lehtilä, A. 1993).
[4] DEA 1995a.
[5] Solantausta & Kurkela 1995.
[6] Solantausta et al. 1996.
[7] STYV 1992.

The efficiency of separate power production based on combustible fuels can be increased to more than 60 % in the longer term (IPCC 1996c). Estimates of the investment costs and efficiencies of some potentially significant new technologies are presented in Table 14. Estimates used in the present study for the technical and economic performance of power production technologies are based mainly on domestic sources, and are discussed in section 5.2 Data from international sources have been used when good domestic estimates have not been available.

Further efficiency improvements could be achieved by expanding the use of combined heat and power production. In the year 1997 the proportion of CHP generation to the total electricity supply was already as high as 30% in Finland. As most of the heat loads suitable for CHP generation are already utilised for combined production, the economic potential for additional increases in the CHP share is not very large with the present technology mix. Possibilities to expand the use of natural gas combined-cycle technologies can be regarded as limited when the security of supply is considered. New solid fuel technologies such as integrated gasification combined-cycle technologies could offer considerable additional potential for efficiency improvements but at present the prospects for rapid commercialisation of these technologies are not perceived to be very good.

Consequently, the potential for CHP is largely affected by assumptions concerning fuel supply and the development of new energy technologies. Some

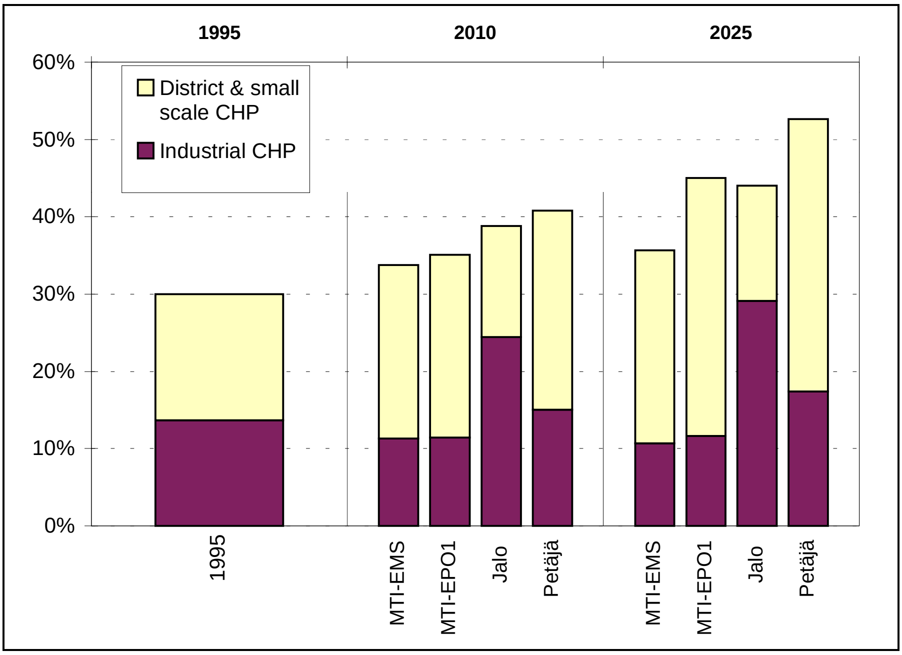

Figure 8. Share of combined heat and power production of total electricity supply in 1990 and in the scenarios of MTI (MTI 1997a), Jalo (Sipilä 1994) and Petäjä (Vehmas et al. 1998) for 2010 and 2025.

scenarios for the future contribution of CHP are presented in Figure 8. In the present study the economic potential of CHP is primarily determined endogenously by the calculation model under externally defined constraints concerning, for example, peak utilisation times, minimum proportions of heat production in non-CHP plants, and penetration of new technologies.

Fuel switching to low-carbon or renewable fuels

Among fossil fuels, natural gas has the lowest CO_2 emissions per unit of energy. The carbon dioxide emission of natural gas is about 40% lower than that of coal, and about 25% less than that for oil. Furthermore, the lower carbon-containing fuels can usually be converted more efficiently into electricity or heat, which has a pronounced effect on the differences in the emission factors. However, in Finland geographical factors restrict the expansion of natural gas use. The present gas network covers only part of southern Finland, but could be extended to the consumption areas of Turku and Pori and Jämsä-Jyväskylä with a reasonable amount of investment. The total potential for industrial and tertiary (incl. district heat and power) consumption of natural gas within such an extended network has been estimated to be about 5.2 billion m^3 in 2010 [1]. Extensions further north would hardly become economical unless a major gas pipeline would be constructed e.g. from the Barents sea to central Europe through Finland.

Apart from industrial and tertiary consumption, natural gas could be substituted for coal in central electricity generation. A heavy reliance on natural gas would require a secure gas supply. If the gas supply remains totally dependent on the pipeline from Russia, substantial investments in reserve storage and plant capacities may be required. Consequently, the economic potential for the use of natural gas is highly dependent on the assumptions made about the development of the Nordic gas market. In the scenarios analysed in the present study, two different assumptions have been made. In the conservative case one assumes that the Finnish gas network remains isolated from the western European gas network during the whole study period. In the more optimistic case a connection through Sweden is assumed to be available around 2010.

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[1] Unpublished study made by Ekono Ympäristötekniikka in 1992.

Table 15. Summary of the bioenergy use in 1995 and the estimated production potentials in 2010 (adapted from Alakangas 1997, except for SRC).

	Use in 1995	**Production potential in 2010**	
	PJ	**Technical, PJ**	**Economic, PJ**
Wood fuels			
Forest residues	7.7	77	27
Thinnings	0.0	36	25
Bark [1]	36.3	45	45
Wood waste [1]	9.9	16	16
Pulping liquors [1]	108.8	150	150
Firewood	37.9	65	49
Wood total	200.6	389	312
Energy crops and straw			
Reed canary grass [2]	0.0	30	5
Coppices (SRC) [2]	0.0	30	1
Straw	0.0	28	6
Crops total	0.0	58	12
Other waste			
Refusal (REF)	0.6	20	10
Biogas	0.7	20	5
Construction waste	6.8	10	8
Waste total	8.1	50	23
Grand total	208.6	497	347

[1] Amounts proportional to the production volumes of forest industries.

[2] Technical potentials for energy grass and SRC are mutually exclusive.

Several studies have been conducted on the production and consumption potential for renewable fuels during the past few years (e.g. Järvenpää et al. 1994, Helynen & Nousiainen 1996, Sipilä et al. 1997, Alakangas 1997). Estimates for the production potential are summarised in Table 15. By far the most significant potential in Finland is related to the use of wood biomass for energy. In addition to the by-product fuels and firewood, the potential from forest residues and thinnings could theoretically be over 300 PJ (Asplund 1997). However, technical and ecological constraints limit the feasible technical potential as shown in Table 15.

Unfortunately, no serious attempts to estimate the present and future supply-cost curve have yet been made in any of the studies. In the present study the end-user price of 60 FIM/MWh or about 17 FIM/GJ has been assumed to represent an upper bound for the economic potential. Accordingly, utilisation of the technical potential over and above the economic potential has been assumed feasible, but the costs have been set at a higher level than 60 FIM/MWh. The total potential of additional wood-biomass supply has been further divided into four different price categories, of which two fall strictly into the range of economic potential.

The economic potential for energy crops has been estimated to be relatively small in Finland. Although the total area of set-aside fields is estimated to be 0.5–1 million hectares by 2005, only a small part of it is judged to be suitable for energy crop production. In Finland short rotation forestry is not considered to have any significant role in the energy supply. This is in sharp contrast with Sweden, where willow is already produced on 20,000 hectares and the total production potential for short rotation coppices is estimated to be about 165 PJ (SOU 1992). As Finland has abundant resources of forest biomass, production of energy wood in the fields is not viewed as necessary. Instead, about 100,000 hectares of cultivated land will be afforested over the next ten years in order to further increase the conventional wood production (Alakangas 1997).

Energy crops that are assessed to have some economic potential in Finland include reed canary grass, as well as turnip rape and barley for liquid fuels production. Among all the options for the production of agrobiomass, straw is estimated to have the lowest production costs. An important factor for policy-makers is also the CAP subsidy system of the EU, which could offer a strong financial incentive particularly for energy grass production. Additionally, the harvesting equipment and schedules for straw and energy grass can offer synergetic advantages. Table 16 summarises some recent cost estimates for agrobiomasses.

Switching to nuclear energy

The introduction of nuclear power in Finland contributed to a major decrease in the Finnish greenhouse gas emissions in the early 1980s, as shown in Figure 2 in Section 2.1. Since then the share of nuclear power in the total electricity supply

Table 16. Cost estimates for the production and short transport of reed canary grass (RCG, willow (SRC), and straw (cost data from Sipilä et al. 1997).

	Baled RCG	**SRC chips**	**Baled straw**
Yield, t(dm) / ha	5.5	9	2
Production costs, including 20-25 km transportation, FIM95 / t(dm)	307	240	208
LHV, GJ / t(dm)	17.13	18.42	17.40
Moisture, %	25.0%	45.0%	30.0%
Effective LHV, GJ / t(dm)	16.2	16.2	16.2
Total costs, FIM95 / MWh	68	53	46
Energy yield, GJ / ha	89	146	32

has slowly decreased, and was about 27% in 1997. As the nuclear share is not very high, additional nuclear base-load capacity would fit in well with the supply structure. The operating experience of the existing Finnish nuclear plants has been remarkably good, and therefore also the projected economics of possible new installations are considerably more favourable than in most other European countries.

The specific investment costs of new nuclear plants have been estimated at 11800 FIM/kW$_e$, and the total operating, fuel and waste management costs at 57 FIM/MWh at the price level of 1996 (Ekono 1997). Therefore, assuming that the economic life of the plant is 25 years, the total generating costs at the station bus-bar would be 160–170 FIM/MWh, depending on the actual load factors. Together with large coal and natural gas combined-cycle power plants, nuclear power is thus estimated to be one of the lowest-cost options for separate power generation. This means that as a greenhouse gas mitigation measure nuclear power appears to be economically a very low-risk option in Finland. However, because of the other risks perceived by the general public, in the present study the nuclear option has been taken into account only in very few scenario variants.

Switching to renewable non-combustible energy sources

Non-combustible renewable energy sources include, basically, hydro, wind and solar energy in Finland. About 13 TWh of hydro power (2950 MW) were already installed in Finland by 1998. Large increases in the production capacity

Table 17. Estimates for the potential and present cost levels of solar and wind energy systems in Finland (Lund 1997).

	Potential TWh / a	**Present cost level FIM96 / MWh**
Solar power		
Integrated in buildings	1	2000–3000
Power plants	2–3	3000–6000
Solar heat		
Summmertime district heat	2–3	150–400
Seasonal heat storage	4–5	600–1000
Wind power		
Coastal areas	4	250–300
Archipelago	10	250–400
Offshore on cliffs, south-coast	3	250–500
Northern mountains	13–15	200–250

are prohibited by environmental protection laws. Nevertheless, small increases can be realised by renovations, or by installing new turbines to existing or decommissioned plants (Kovanen 1992, Salokoski & Äijälä 1996). According to the scenarios published by the Ministry of Trade and Industry (MTI 1997a), the normal-year hydro power production could be about 14 TWh in 2010. No increases were assumed in the MTI scenarios after 2010, but one could assume continuing slow increases to be possible also thereafter. Therefore, in the present study the total production is assumed to be 14.2 TWh in 2020, and 14.7 TWh in 2040. This assumption is taken to be as a fixed scenario.

According to a recent summary review, the potential for wind and solar energy can be estimated as shown Table 17 (Lund 1997). In the medium term (until about 2015), only wind power can be expected to have a notable role in the total energy supply. In the long term both solar heating and solar power systems can be expected to become competitive, at least in special niche markets. Nevertheless, because the economy of solar energy is, in Finland, inherently weakened by geographical conditions, the role of domestic solar energy systems can be expected to remain marginal for quite a long time (MTI 1997b).

Due to different approaches to land-use restrictions, there are several diverging estimates of the potential for wind power on land and within the archipelago areas. However, the maximum wind power potential can be reasonably well assessed until the year 2010. At the end of 1998 the total wind power capacity was about 20 MW, and existing plans suggest that the capacity could be at most 50 MW in 2000. Based on the scenarios presented in recent surveys (Lund 1997, Ekono 1998), the capacity could be 150 MW in 2005, and about 400 MW in 2010. Recalling that the average number of full-load hours has been about 2200 in Finland, a realistic maximum estimate for potential wind power output in 2010 would be 0.9–1 TWh.

In the longer term, the potential on the mainland and in the archipelagos has been estimated to be about 6 TWh in areas with no land-use restrictions according to current regional plans (MTI 1993, Peltola & Petäjä 1993). Further potential can be found on mountains in the northern part of Finland, and by utilising offshore wind energy. The practical potential for arctic wind power on the mountains has been estimated to be 1–2 TWh (MTI 1993). According to the surveys made, the economics of offshore wind energy would in Finland be best for plants installed on small cliffs. Taking into account the restrictions induced by the existing power grid, the total potential for such plants has been estimated to be about 3–4 TWh (Sommardal et al. 1994, Holttinen 1998).

The costs for wind power production have been decreased remarkably during the past two decades. By the year 2020 the investment costs are expected to be further decreased by about 30 % (Ekono 1997, DEA 1995b). The costs of on-grid solar power systems have been decreasing even more rapidly, but the decrease has slowed down considerably during the last decade. The investment cost are still over 30,000 FIM/kW (Ekono 1998). Nevertheless, large programmes have been initiated in some countries (e.g. USA and Japan) to promote the integration of solar power systems with building structures. In such systems the total costs can be reduced by substituting solar panels for conventional facade materials (Lund 1997).

The wind power potential taken into account in the present study is in line with the estimates presented above. For solar power, only small-scale on-grid photovoltaic systems, which are not integrated into building structures are considered in the study. This is due to the lack of sufficient data on the costs and energy yields of integrated systems. Additional information on the assumptions used for wind and solar energy is given in Section 5.2.

Recovery and disposal of CO_2 from flue gases

It is quite feasible to remove and store the CO_2 from the flue gases of a fossil fuel power or heat station. The main drawbacks are that the conversion efficiencies are reduced and the production costs are increased significantly. It has been estimated that a removal of 87% of the CO_2 in the flue gases of a conventional coal power plant would reduce the energy efficiency from 40% to 30%, and increase the costs per unit of electricity by about 80% (IPCC 1996c). The increase in costs would thus correspond to about 200 FIM per tonne CO_2 removed. This cost does not, however, include the costs for the storage, transportation and final disposal of the recovered CO_2. Similar estimates of the cost increases have been reported in a Finnish survey (Salokoski & Äijälä 1996).

If the costs for storage and final disposal were small, CO_2 removal could well become one of the cost-effective technical measures to reduce CO_2 emissions under tightening greenhouse gas emission targets. Potential alternatives for the final disposal include deep ocean repositories, and oil and gas fields. Consequently, countries like Finland would have to transport the CO_2 recovered for very long distances. Furthermore, there are still quite a few unanswered technical questions related to the final disposal of CO_2. In any case, the costs for transportation and final disposal would be very high for CO_2 recovered in Finland. If the option should become cost-effective, the practical solution for Finland would be to replace domestic electricity production by imported electricity produced close to oil or gas fields amenable for CO_2 disposal, e.g. from Norway. As the possibilities for such arrangements are as yet very speculative, the option of CO_2 recovery and disposal has not been taken into account in the present study.

4.1.2 Industrial sector

In this study the industrial production of electricity and process heat is grouped under the energy sector. Therefore, the measures for reducing carbon dioxide emissions discussed in the previous section cover for a large part also the measures applicable to industrial energy use. Apart from measures related to power and heat generation, IPCC suggests the following technical options for reducing industrial greenhouse gas emissions (IPCC 1996c):

- Introduction of new process technologies
- Improvements in existing processes
- Thermal cascading
- Material substitution
- Material recycling.

The introduction of new process technologies typically involves large capital investments, and is therefore normally governed by the natural production capacity retirement rates. Nevertheless, the turnover of capital is typically somewhat more rapid in the industrial sector than in the energy sector. According to the IPCC, the most energy-efficient industrial processes in the chemical or primary metals industry today consume energy three to four times their thermodynamic energy requirement. That would leave considerable room for efficiency improvements.

Improvements in existing processes can involve just fine-tuning the process e.g. by introducing better control systems to reduce wasted energy. Other measures could be directly related to the fuel choices and thus also emissions. For example, in the production of ammonia, natural gas can be replaced by biomass as the feedstock source of hydrogen. Thermal cascading means the recovery and utilisation of lower temperature heat for appropriate purposes, thus reducing the amount of heat wasted. In Finland such techniques are already in wide use in many branches. Finally, material substitution and material recycling represent potentially very large possibilities for reducing energy use. For example, the use of wood as a construction material instead of concrete can reduce the embedded energy use by as much as 95% (IPCC 1996c). Recycling materials whose manufacturing process is very energy-intensive can also in many cases reduce the energy consumption by more than 50%. This is particularly true for several primary metals (e.g. aluminium), but for many other materials recycling causes unavoidable downgrading in quality, which reduces the achievable energy gains.

In the present study the industrial measures for greenhouse gas abatement include primarily various energy conservation measures applicable to the production processes. Only measures related to the consumption of power or process heat have been considered, i.e. the intensities of direct uses of fuels such as coke combustion in blast furnaces have been described with fixed scenarios. Options for new process technologies have been taken into account insofar as the transition from existing technologies to the new ones can be assessed not to involve high financial risks. Options related to changes in the product mix have generally not been taken into account, due to insufficient possibilities to evaluate the economic implications of such changes   The processes and product mixes, e.g. in the forest products industry and basic metals manufacturing are defined as fixed scenarios and are not determined through cost-effectiveness considerations.

Estimates for the potentials of energy conservation measures have been reported in numerous domestic studies. The most comprehensive study was the Energy conservation project finished in the early 1990s (Lepistö 1991), but the results from the various sectoral analyses of the study can to a large extent still be assumed to be applicable (e.g. Rintekno 1990, MTI 1990).

According to a survey made in 1995 (Timonen 1995), and a product level analysis made during the present study, the specific energy consumption of forest industry products generally increased slightly during the early 1990s, but have thereafter remained stable or returned to the 1990 levels. A notable exception is mechanical pulping where specific electricity consumption has continuously increased due to requirements for finer qualities. In the basic metals manufacturing a decrease of about 2% in specific product-level electricity consumption has been achieved in five years. The consumption of heat has decreased considerably, but as it is in any case quite small, no explicit conservation measures are considered. In the chemical industries, electricity consumption per value added was in 1995 almost at the same level as in 1990, and heat consumption had slightly increased due to changes in product structure (see Appendix B). However, according to the 1997 results from the Responsible Care Programme (Chemind 1998) the electricity consumption of major chemical industries was in 1997 reduced by 24% compared to the previous year in proportion to production volumes. The corresponding reduction in other energy use was as high as 39%. Because the information has been very preliminary,

Table 18. Estimates for the potential and costs of energy efficiency improvements in the industrial sectors (Lepistö 1991).

	Best commercial technology		Including best prototype technologies
	Potential %	Cost (5% rate) FIM90/MWh	Potential %
Electricity			
Forest industries	9%	n.a.	21%
Chemical industries	5%	130–140	13%
Basic metals manufacturing	5%	n.a.	29%
Other manufacturing	14%	10–130	18%
Process heat			
Forest industries	15%	n.a.	21%
Chemical industries	13%	50–450	23%
Basic metals manufacturing	1%	n.a.	13%
Other manufacturing	18%	0–110	24%

these reductions have not been taken into account in the present study (insufficient official statistics available). Consequently, the future energy intensity of chemical industries may be somewhat overestimated in the present study. In other industrial sectors the changes in specific energy consumption between 1990 and 1995 appear to be in general relatively small, although notable changes have occurred in many industrial branches during the intermediate years of recession.

Table 18 summarises the estimates from the Energy conservation project concerning industrial sectors. For the potential in forest industries, a number of additional studies in the national energy research programmes have also been used (e.g. Sundholm 1994, Paulapuro & Komppa 1994, Lähepelto 1996). For the chemical industries, the sectoral analyses of the Energy conservation project have been the main source (Rintekno 1990). For basic metals manufacturing the results from the SULA Programmes (Hakulin 1994) have been taken into account.

The results from the Energy conservation project indicated that from the viewpoint of the whole energy economy substantial no-regret potential for efficiency improvements could be found in most end-use sectors. In practice, however, such potential is not being utilised. This has been explained mainly by the rate of return required, which for various reasons is often set on a very high level by individual economic agents. The high requirements for the rate of return often reflect true cost overheads resulting e.g. from case-by-case uncertainties and productivity losses during implementation, but can also be related to institutional barriers or insufficient information in the decision-making processes.

Neither the costs actually perceived by economic agents nor the true implementation costs can be easily estimated. Nevertheless, the cost assumptions should be reasonably consistent with the actual behaviour of the agents. Therefore, in this study all the costs of the energy conservation measures considered have been calibrated to be higher than the break-even point in the baseline energy system, while attempting to preserve the shape of the original cost function estimate. With such a calibration results that would indicate unrealistic cost-savings form energy conservation measures can be avoided. More detailed information on the costs and potential of the measures in each sector is given in Section 5.3.

4.1.3 Residential and tertiary sectors

The energy consumption in the residential and tertiary sectors include energy used for space heating, hot water, cooking, lighting and various appliances. The technical options can be divided into four categories:

- Switching to less carbon-intensive energy sources in heating and cooking
- Improvements in thermal integrity
- Efficiency improvements to heating, cooling, and hot water equipment
- Efficiency improvements to cooking, lighting and other appliances.

All the options in the last three categories can be considered as energy conservation measures. However, in the present study the gradual improvements in the efficiency of each type of heating and hot water equipment are defined as fixed scenarios, and are not included in the measures considered explicitly. Similarly, the autonomous improvements in the thermal integrity of buildings through new construction or renovations are not considered as options, but are given exogenously as scenarios.

The explicit options considered for heating and hot water consumption can be divided into switching between different heating systems or heat sources, and into measures for improving thermal integrity. Estimates for market shares in heating in 1995 are presented in Figure 9. The market share of district heating is generally expected to be slowly increasing, as is the share of electric heating in single-family houses. The shifts in market shares from such a baseline estimate cannot be expected to be very large, mainly because of the slow turnover of the capital stock. Up-to-date cost estimates for various conventional heating systems have been presented e.g. in a survey made at VTT Energy (Flyktman 1996).

According to the Energy conservation project, in addition to the autonomous efficiency improvements there still exists potential for considerable improvements in thermal integrity. Estimates for the total efficiency improvement potentials are shown in Table 19 together with the estimates for household and tertiary electricity consumption. The estimates for new buildings are well in accordance with more recent studies (e.g. Saarimaa et al. 1994). In a recently published baseline scenario (MTI 1997a) the average specific heat consumption is expected to decrease by about 10% by 2010, and by about 15% by 2025. Even if the total potential were also to include efficiency improve

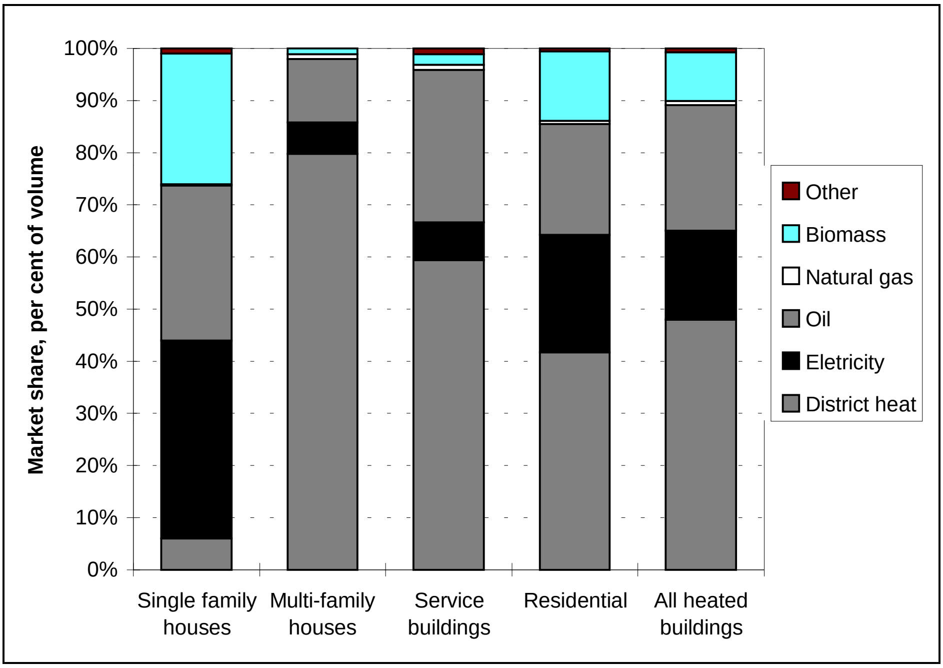

Figure 9. Market shares of different energy sources in space and water heating in 1995, as percentages of total building volume.

Table 19. Estimates for the potential and costs of energy efficiency improvements in the residential and services sectors (Lepistö 1991).

	Best commercial technology		Including best prototype technologies
	Potential %	Cost (5% rate) FIM90/MWh	Potential %
Existing building stock			
Single-family houses	26%	270	41%
Multi-family houses	24%	220–330	40%
Service buildings	35%	160	56%
New buildings			
Single family houses	33%	310	53%
Multi-family houses	25%	270–280	45%
Service buildings	42%	170	69%
Household electricity	47%		65%
Lightning	70%	170–380	76%
Cold storage	64%	80	64%
Other appliances	33%	30–200	62%
Services electricity	40%		50%
Lightning	58%	~100	65%
Cold storage	25%	~100	63%
Other appliances	30%	~100	38%

ments in the heating systems, the additional potential for improving thermal integrity can be estimated to be quite large, about 20–30%. As in the case of the industrial sectors, in the present study the costs of the conservation measures have been calibrated against the baseline scenario. The assumptions are described in more detail in Section 5.3.

Apart from the more conventional heating systems, potentially important new technologies include, in particular, heat pumps and solar heating systems. The potential for solar heating in single-family houses is estimated to be relatively small (Lund 1997), but when combined with the estimates for large-scale solar heating, the total potential would be about 7 TWh. As in the present study only solar heating integrated into single-family houses is considered, it would be reasonable to include some of the potential estimated for larger-scale production. Therefore, a maximum potential of about 3 TWh has been assumed for 2040. The investment costs for a solar water-heating system in 1995 were about 2600 FIM/GJ a^{-1} higher than for an electric boiler system, and the costs for a complete solar heating system have been estimated to be about 3000–4000 FIM/GJ a^{-1} (Leppäniemi et al. 1995, DEA 1995b). The investment costs per unit of useful heat produced are expected to decrease by at least 35 % and possible by as much as 60 % by the year 2020 (DEA 1995b).

In Finland there are only about 10,000 heat pumps installed in detached houses, while in Sweden the amount is about 300,000. Furthermore, in Sweden a target of doubling the amount in the next 15 years has been set. On the basis of these figures, the potential in Finland could well be estimated to be 200,000 – 300,000 houses. The optimal size of a heat pump is generally estimated to be about 50% of the peak load, corresponding to about 90 % of the annual heat consumption. Consequently, 250,000 houses (22 % of all detached houses in 2010) would represent about 20% of the total heat consumption of detached houses in 2010. In the present study only ground heat pump systems are considered for detached houses. For service buildings exhaust-air heat pumps are assumed to be the most applicable option. The investment costs for a ground heat pump system per unit of annual useful energy produced were about 1200–1500 FIM/GJ a^{-1} in 1998 (Leppäniemi et al. 1995). As the market for heat pumps has not yet been matured and the technologies are still evolving, the investment costs per heat output can be expected to decrease by about 10 % by the year 2020 (DEA 1995b).

Exhaust-air heat pumps can be considered for commercial buildings and also for multi-family houses. The costs of air heat pump systems are much lower than those for ground heat pumps. In 1998 the investment costs were 500–700 FIM/GJ a^{-1} (per unit of useful heat produced annually), i.e. about twice as much as for direct electric heating. The long-term potential is, in this study, estimated to be 10 % of the total consumption of space heat in service buildings and 5% in blocks of flats.

4.1.4 Transport sector

On a global scale, energy use in transportation has grown more rapidly than in any other sector. In Finland, transportation accounted for about 20 % of the total energy-related carbon dioxide emissions in 1996. The technical options available for reducing carbon dioxide emissions from transport include efficiency improvements, alternative energy sources, urban planning and infra structure, as well as modal shifts. In a small country the possibility of influencing the technical development of transport vehicles is quite small. Therefore, in the present study the energy efficiencies of all transport vehicles have been defined as fixed scenarios.

The most promising alternative car concepts are electric cars, hybrid cars, and fuel cell cars. In addition, methanol, compressed natural gas and liquefied petroleum gas could be used as fuels in conventional types of car engines. In the long term the fuel cell technology probably could offer the best combination of efficiency and flexibility. The alternative car concepts considered in the present study include electric passenger cars and vans, as well as methanol, compressed natural gas and LPG cars. As only highly tentative estimates can yet be made for fuel-cell cars, the electric car will serve as representative of both.

Because even electric cars are still in the experimental phase, quite limited information is available about their present or future costs. A rough estimate of the present price-level is 1.5 times that of a gasoline car of similar class. Nevertheless, one could estimate that the investment costs will eventually be reduced to close the levels of conventional ICE cars. For the alternative fuel cars, cost estimates from an unpublished German database have been used (Ruß et al. 1991). However, using the cost data that have been available appears to render electric (or hybrid) cars to be the only cost-effective technical option for CO_2 mitigation in passenger transport in the medium term.

Some energy saving can be achieved by improving driving styles and decreasing unnecessary consumption. In the Energy conservation study such non-technical energy conservation potential was estimated to be about 5% (Lepistö 1991). Accordingly, a small potential has also been taken into account in the present study. The potential could be viewed as being related, for example, to making use of adaptive driving control and monitoring systems, which could provide up to 15 % reduction in fuel consumption [1].

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[1] Motiva Information Centre for Energy Efficiency, November 1998. (http://www.motiva.fi/motiva/lii-econen.html)

4.2 Abatement of methane emissions

4.2.1 Recycling and waste incineration

The most efficient measure for CH_4 abatement in the waste management sector is reducing the amount of landfill waste. In Finland this is the main objective of the national waste plan (Ministry of the Environment 1998). The purpose is to increase considerably the utilisation rate of waste by the year 2005. The CH_4 abatement is not the only reason for lessening the amount of landfill waste. Waste disposal sites have also other disadvantageous environmental effects, such as pollution of water systems.

An important factor in the comparison of cost-effective CH_4 reduction measures is the cost of landfill, which can be considered as a reference cost. The costs vary in different parts of Finland due to transportation distances of different length. On average the total cost of the disposal of municipal solid waste is roughly 750 FIM/ton. This estimate is based on Tanskanen (1996).

The current and estimated future utilisation rates of the significant municipal solid waste (MSW) fractions for methane emissions are presented in Table 20.

An exact estimate was available only for the current utilisation rate of paper and board (Finnish Environment Institute 1997). The current utilisation rates of organic waste and combustible fraction are based on Tanskanen (1996, p. 57). Combustible fraction (source-separated recycled fuel, REF) contains paper, board and plastic, which are not suitable for recycling; for example packing materials. The utilisation of organic waste is discussed in Sections 4.3.2 and 4.3.4.

Table 20. The present utilisation rates for significant MSW fractions, estimates for the year 2005, and utilisation measures.

Fraction	**Present**	**in 2005**	**Utilisation measure**
Organic waste	10–20%	20–75%	Composting or anaerobic treatment
Paper and board	61%	60–75%	Recycling, as a fuel
Combustible	ca. 5%	< 70%	As a fuel

The most important recycled materials in Finland are paper and board, which have been widely utilised in the paper industry. It is assumed that in the future the utilisation rate of paper and board will be at least at the present level. The costs due to recycling have been estimated with help of Tanskanen (1996). The cost estimate includes waste containers, collecting and transportation; and the total is on average about 600 FIM/ton.

The burning of REF is done in the boilers of the existing power plants, together with other fuels. It has been estimated that the lower heat value of REF is about 18 MJ/kg (Pipatti et al. 1996). Because of a relatively low heating value, it is reasonable to incinerate REF in fluidised bed boilers. The fuel cost of REF is about 800 FIM/ton (160 FIM/MWh), and it includes waste-container, collection, transportation, and treatment costs[1]. In the treatment phase the source-separated waste is crushed into smaller pieces, so that the waste requires less space and the utilisation in boilers is easier. It has been assumed that the incineration of REF with other fuels does not increase the costs of existing power plants.

Municipal solid waste can be utilised directly as energy by mass incineration, which is done in waste incineration plants. In Finland there is only one waste incineration plant in Turku. Its annual capacity is about 53,000 tons. It has been estimated that at most about 90 per cent of MSW is suitable for mass incineration. The lower heat value of MSW is about 11 MJ/kg wet waste. The methane emissions due to incineration are insignificant compared with the ones due to landfill. (Pipatti 1997; Pipatti et al. 1996). The power plant costs of mass incineration have already been described in the EFOM model prior to this study. Other costs needed are that of the waste-container, collection, and transportation costs of MSW, which altogether are about 650 FIM/ton.

In the future gasification (pyrolysis) is also one possibility for utilising the energy content of waste. Lahden Lämpövoima Oy (a power company owned by the city of Lahti and Imatran Voima Oy) has been testing a 40–50 MW circulating fluidised bed gasification plant connected to a 350 MW steam boiler fired by coal and natural gas. The gasifier has been tested with wood-based

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[1] The cost data is mainly based on personal communication with Sirje Ingervo, YTV. The waste container costs have been estimated with help of Tanskanen (1996).

fuels, and a future objective is to burn REF and peat. The product gas is utilised in a steam boiler to replace fossil fuels. Unfortunately, the cost data have not been available. (Wilén and Kurkela 1997; Haukkasalo 1998)

4.2.2 Landfill gas recovery

The CH_4 emissions from landfills can be reduced by landfill gas recovery. The common recovery system consists of intake wells, collection pipes, collection wells and compressor pump, which provides the necessary suction for the system to recover landfill gas from the waste layers. From the compressor facility gas is directed to utilisation or to the torch. Landfill gas must be purified, especially before utilisation. (Pipatti et al. 1996) In the Netherlands landfill gas is injected directly into the local natural gas grid. In this case CO_2 and impurities must be separated out (Oonk and Boom 1995). Gas formed in the waste layers contains roughly 50 per cent of methane and 50 per cent of carbon dioxide. These proportions vary with different landfills and with different composition of waste. In Finland the lower heat value used in calculations is 4.5 kWh/Nm^3. [1]

The total recovery efficiency depends on the timing of the start of the recovery. Usually the recovery is begun after closure of the landfill, in which case a part of the total methane potential is already emitted into the atmosphere. On the other hand, the recovery begun during the operation period is becoming more common. After the installation of the recovery system, 50–90 per cent of formed landfill gas can be recovered. In this study a recovery efficiency, 50 per cent, is used, because the amount of emitted landfill gas calculated by the mass balance model (see Section 2.3.2) might be somewhat too high. The aim of this choice of method is to get a reasonable estimate for recovered amount of energy.

In Finland recovery equipment has been installed in 8 landfills, and more of them will be installed in the future, because according to the law it is necessary to recover landfill gas from new landfills. Old ones have a transition time, which will last until 2002 (The Finnish Council of State, 1997). However, the law is

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[1] This value, other data considering the efficiency and the costs of landfill gas recovery, and data for gas engines are based on personal communication with Petri Väisänen, Sarlin-Hydor Oy.

Table 21. The costs of the recovery system.

	Big disposal site	**Small disposal site**
Investment costs (FIM/GJ/a)	75.6	87.2
Torch (FIM/GJ/a)	7.7	
Operating costs (FIM/GJ)	2.5	2.5

not unconditional, because the environmental authorities have the right to consider the cost-effectiveness of landfill gas recovery case by case. As a result the recovery system is probably not installed in every landfill, but only in landfills where it is economically reasonable. Many of small landfills will be closed in the near future, and therefore the recovery systems will be installed mainly on big landfills.

The recovery costs are presented in Table 21. The costs of big disposal sites are based on an estimation, which has been done for a disposal site, in which about 500 Nm^3 landfill gas is emitted per hour. The investment cost (2.45 MFIM) is converted to cost per capacity unit (GJ/a) with 50 per cent recovery efficiency and 8000 h/a operating time. The operating costs (0.04 FIM/Nm^3) include the electricity consumption of the compressor pump and the maintenance of the system. If the recovered gas is burned in a torch, the investment costs (0.25 MFIM) of the needed facility have to be taken into account too. The quality of the cost and efficiency data for landfill gas recovery can be assessed to be reasonably good, as they are based on many operational recovery systems.

In small disposal sites, where the production of gas is about 200 Nm^3/h, the utilisation of landfill gas as energy is usually not economical, and therefore gas is burned in a torch. The costs of the torch are included in investment costs. The operating costs are estimated to be the same as in the case of big disposal sites. Generally, the recovery costs have been quite stable for some years.

In big landfills the recovered landfill gas can be utilised in energy production in various ways. In Finland operational options are, nowadays, direct combustion in heating boilers and use in stationary gas engines. The heating boilers are either manufactured for this purpose or modified from oil-fuelled boilers. The gas engines are used mainly for electricity production. Co-generation of heat and power is also possible with the waste heat boiler. The gas engines are turbo-charged Otto cycle-cycle engines, and so the fuel does not need to be

Table 22. Economical and technical data of the gas engine.

Investment costs of electricity production (FIM/kW$_e$)	5500
Investment costs of heat production (FIM/kW$_{th}$)	500
Operational costs (p/kWh)	7.0
Peaking time (h/a)	8000
Power-to-heat ratio	0.6

pressurised as, for example in the gas-diesel engines. In electricity production 38 per cent efficiency is achieved. In the heating boilers, only heat is produced with about 90 per cent efficiency. In the future the dominant utilisation technology is probably the gas engine, which produces only electricity, because the utilisation of heat outside the disposal site requires nearby district heating grid or another heat consumer. A part of the produced energy is often utilised in the disposal site area in different applications (e.g. compressor pump and lighting). It has been assumed that the proportion of the own use of energy is about 30 per cent.

The costs of using gas engines are presented in Table 22. The costs are suitable for 0.5–1 MW$_e$ engines, which are the typical sizes used in the disposal site. The investment costs of heat production are mainly due to the waste heat boiler. The operational costs include personnel, lubricant and maintenance costs. The costs of combustion in heating boilers are already implemented into the database of the EFOM model, and so they are not presented in this study.

4.2.3 The composting of organic waste

Composting is a simple and environmentally friendly technology for reducing the amount of organic waste in landfills and, consequently, CH_4 emissions. The amount of methane emitted from composting is insignificant compared with the emissions due to landfill, because the waste is kept in aerobic conditions. The emissions are very small, even if the composting would function poorly. The product from composting is humus, which can be sold. (Pipatti et al. 1996)

Composting of organic waste is becoming more common, because according to the law it will not be permissible in the future to deposit high organic content waste into landfills (The Finnish Council of State 1997). Nowadays about 10–20 per cent of organic waste is composted. It has been estimated that at most 75 per cent of organic waste can be composted, because organic waste requires source separation, which probably never functions completely.

The composting is nowadays done in stacks or in tunnels in specific composting plants. The latter method has recently become more common, and in the future it will probably be the dominant technology. In stack composting the organic waste and some back material (bark, peat, wood chips, etc.) is spread on the ground in the stacks, which are covered. In tunnel composting the organic waste is deposited in steel concrete tunnels, which can be closed. In order to maximise the production of composted material, air is blown underneath the tunnels.

The investment and variable costs of a composting plant are in total about 500 FIM/ton of organic waste[1]. The costs of stack composting are about 200 FIM/ton. In addition, waste container, collection, and transportation costs (about 560 FIM/ton) must be taken into account. (Tanskanen 1996)

4.2.4 Anaerobic treatment of animal manure and organic waste

The anaerobic treatment applies to the CH_4 abatement of waste management and agriculture. In anaerobic treatment, manure and other biomass are decomposed in specific reactors under anaerobic conditions. When only manure is processed, the output of biogas is lower, because the nitrogen-carbon ratio of manure is too high for optimal forming of biogas. Therefore it is reasonable to process some organic waste too. These biogas plants produce humus and biogas, which contains about 65 per cent methane. Humus can be applied, for instance, to the fields of the cattle farms. Biogas is recovered and it can be utilised in the production of heat and power. The process heat needed in the plant is also produced with biogas. (Lehtimäki 1995; DEA 1992)

In Finland there is only one anaerobic treatment plant, in the town of Vaasa (Tanskanen 1996, p. 44). It processes mainly organic wastes and sludges. Anaerobic treatment of manure is probably cost-effective only in centralised plants, in which case the amount of manure needed is large. The farms are quite small in Finland, and therefore many farms would have to manage manure

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[1] Based on personal communication with Juha Uuksulainen, YTV.

Table 23. The data of anaerobic treatment for plants, which process many types of biomass or organic wastes only.

	Mix	Org. waste only
Investment costs (FIM/t/a)	480	3740[1]
Fixed costs (FIM/ton,a)	21	
Variable costs (FIM/ton)	49	562
Biogas to external energy production (GJ/t)	0.8	2.5
CH_4 recovery efficiency	90%	100%

centrally. For example in Denmark centralised bio-gasification has been common for almost ten years. Both manure and organic wastes are processed in the same plants, which appears to be a suitable option for Finland too. The economic and technical data of the biogas plants are based on Danish Energy Agency (DEA 1992), Lehtimäki (1995), Tanskanen (1996), and Pipatti et al. (1996).

The costs and other data are presented in Table 23. The investment costs are calculated with a five per cent annual interest rate in real terms and 20 years operation time. The costs do not include the costs of the external energy production. The costs of organic waste treatment correspond to the costs of the plant which is in use in Finland (capacity for organic wastes is 6500 ton/a). In addition waste container, collection and transportation costs, which are together about 560 FIM/ton, must be taken into account. The investment costs for the plant, which processes manure and other biomass ("Mix"), are the same as the costs of a Danish biogas plant with annual capacity of 51 kilotons. Transportation costs are estimated to be 200 per cent higher than in Denmark, because of longer transportation distances. It can be seen from Table 23 that the costs of the treatment of organic waste are much higher. The values are not directly comparable, because the plants are of different types.

Danish plants, which process manure and organic wastes, produce on average 36 m^3 biogas/ton of biomass, of which 3 m^3/ton is utilised for process heat in the plant. Therefore 33 m^3/ton can be utilised in the production of external energy. This amount of biogas (6.5 kWh/m^3) is about 0.8 GJ/ton in primary energy terms (DEA 1992). Anaerobic digestion of organic wastes only produces about

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[1] The investment cost includes the fixed costs.

150 m^3 biogas per ton of waste (Pipatti et al. 1996), which corresponds to 3.5 GJ/ton. The proportion of the own use of biogas is assumed to be 30 per cent, in which case about 2.5 GJ/ton is left over for external energy production.

Some methane is emitted from manure e.g. during transportation, and therefore the CH_4 recovery efficiency of “Mix” plants is estimated to be 90 per cent. In the case of organic wastes, the forming of methane does not start as quickly as in the case of manure; although the efficiency might be lowered by, for example, leakage in the case of malfunction. It has also been assumed that at most 50 per cent of organic waste and liquid manure can be treated anaerobically. The sludge from sewage treatment plants is also treated anaerobically, but information about this was not available during this study.

4.2.5 The composting of manure

The CH_4 emissions from manure management can be reduced by composting. The purpose of composting is to keep the manure in aerobic circumstances, in which case no methane will be formed. The best result will be achieved with drum composting, in which the manure is feeded into a circulating horizontal cylindrical drum from one end, and the output is taken out from another. The composted manure can be applied to the fields or it can be sold outside the farm. In 1994 about 50 farms had a drum compost in use in Finland (Klemola and Malkki 1995). The CH_4 reduction efficiency of the drum composting is assumed to be 70 per cent. It has been estimated that it is suitable for at most 80 per cent of farms (Pipatti 1997). In Table 24, the costs of drum composting are compared

Table 24. The costs (FIM/ton of manure) of the different manure management systems (Klemola and Malkki 1995).

System	**Dairy cattle**	**Other cattle**	**Swine**	**Sheep**	**Horses**	**Poultry**
Drum compost (solid)	159	159	151	155	155	133
Drum compost (liquid)	159	159	151			
Solid manure management	61	61	61			
Liquid manure management	87	87	87	87	87	87

with the costs of the present management systems. In the calculation of the costs the amounts of manure produced by different animal categories are also needed and they have been taken from Heinonen (et al. 1992, p. 257).

4.2.6 Other CH_4 reduction measures

Most of agricultural CH_4 emissions are due to enteric fermentation of animals, especially dairy cattle. The abatement of emissions is possible by improving the feed and the animals’ digestive abilities. There have been no studies carried out in Finland on these measures, and so there is, for example, no knowledge of efficiency and costs. However, it has been estimated that there is no significant decrease of emissions in prospect (Pipatti 1997). Thus, these measures are excluded from this study.

The CH_4 emissions from energy production can be reduced by taking advanced combustion techniques on broad use. On power plant scale CH_4 emissions are already very small. Most emissions are due to small-scale combustion from which emissions can be reduced by more advanced stoves and boilers (Carter et al. 1996). Unfortunately, there is no knowledge of the costs and the reduction efficiencies. The emissions from transportation are already very small and they will decrease further, when passenger cars without catalytic converters become less common. Consequently, there is no need to use additional measures to reduce CH_4 emission.

4.3 Abatement of nitrous oxide emissions

4.3.1 Combustion processes

The N_2O emission from the energy sector will increase in the future, because of the expanding use of fluidised bed combustion (FBC) in energy production and catalytic converters in passenger cars. It has been estimated that in 2010 about 50 per cent of Finnish N_2O emissions will be due to the energy sector (Pipatti 1997). In 1990 this share was about 30 per cent.

In fluidised bed combustion N_2O emission reduction is not of great importance, since it is only a small part of the GHG emissions from FBC. The reduction measures are aimed mainly at carbon dioxide and acidifying emissions, such as nitrogen oxides and sulphur dioxide. In principle, the N_2O emissions could be reduced by adjusting the combustion conditions, but in that case other emissions tend to increase (Kilpinen 1995). The main problem in FBC is that the emissions are dependent on each other.

One possible way to reduce N_2O emissions from FBC is to burn natural gas in the cyclone of the boiler, in which case a part of N_2O degrades to molecular nitrogen (Kilpinen 1995). Unfortunately, no knowledge of the costs and efficiency for power plant scale boilers was available during this study.

The N_2O emissions from passenger cars with catalytic converters are considerably greater than the emissions from cars without catalytic converters. In order to reduce N_2O emissions from the transport sector, development in motor and catalytic converter technologies is needed. In addition, the motor vehicle population should be renewed faster than at present (Pipatti 1997). There are no commercialised technical solutions to solve this problem yet and slow renewal of the motor vehicle population makes emission reduction practically impossible.

Reducing NO_x emissions from the energy sector would also decrease indirect N_2O emissions due to atmospheric nitrogen deposition. In the future the NO_x emission reduction objectives, which already have been adjusted in Finland, will be further tightened. Consequently, the N_2O emissions due to nitrogen deposition will probably decrease.

4.3.2 Industry and agriculture

The N_2O emissions from nitric acid (HNO_3) production can be reduced by optimising the manufacturing process, shifting the process to a modern integrated one, and converting N_2O to nitrogen and oxygen by using catalysts. In Finland nitric acid is manufactured by single-phase middle-pressure process, which has an emission factor of 6–7.5 $g(N_2O)/kg(HNO_3)$. Correspondingly, the emission factor for a modern integrated process is about 2 $g(N_2O)/kg(HNO_3)$, hence the emissions could be reduced about by 70 per cent by changing the manufacturing process (IPCC 1997). The cost data for changing and optimising the process were not available during this study.

The most likely reduction measure, which might be taken up in Finland, is the catalysis, whose reduction efficiency is about 70–80 per cent. According to the Dutch study (de Jager et al. 1996), the costs are at the moment lower than the ones of other measures for this purpose. They are estimated to be 800–4800 FIM/ton of reduced N_2O (Oonk 1998) or 4–23 FIM/ton of manufactured HNO_3. However, there are no commercial scale experiences yet.

The estimation of the agricultural N_2O emission reduction is very uncertain due to many combined effects which contribute to the amount of emissions (Pipatti 1997). Reductions are probably possible by optimising the timing, techniques and the amount of fertilising (de Jager et al., 1996). In any case, these measures are excluded from this study.

5. Calculation model

5.1 Overview

For the energy-system calculations needed in the study, a large energy system model has been used. The methodology of the model is based on the widely-used technology-oriented bottom-up approach, which applies integrated cost-optimisation to the national energy system as a whole. In terms of model implementation, the model belongs to the family of EFOM models, which have been used for instance in the EU-wide study 'Cost-effectiveness analysis of CO_2 reduction options' under the CEC DG XII (CEC 1991). Another widespread family of models of the same general type is the MARKAL modelling approach originally developed under the IEA ETSAP Programme.

The EFOM model is basically a quasi-dynamic many-period linear optimisation model. It has a modular structure consisting of identifiable subsectors of the energy system as depicted in Figure 10.

The model is best suited for the representation of identifiable technologies which have or potentially could have a notable role in the energy system. These are either large-scale technologies, such as power plants, or small-scale technologies used in large quantities, such as space-heating systems, cars, lighting systems or refrigerators. The supply subsystems and heavy industries are dominated by large-scale technologies, which can be adequately described in the model. However, in the case of oil refineries and light industries the processes and products involved are quite diverse and large in number so that the modeller is forced make a choice between a rudimentary or a very detailed description. In the Finnish EFOM model the refineries and light industries have been described on a very general level only.

By using the model, the development of the energy system can be studied over a period of up to 30–40 years. In order to simulate the dynamics of the energy system, the total study period is divided into sub-periods. The characteristics of the existing residual equipment and the available technologies for new equipment can be described individually for each sub-period. The model solution includes the states of all model variables (e.g. energy flows and

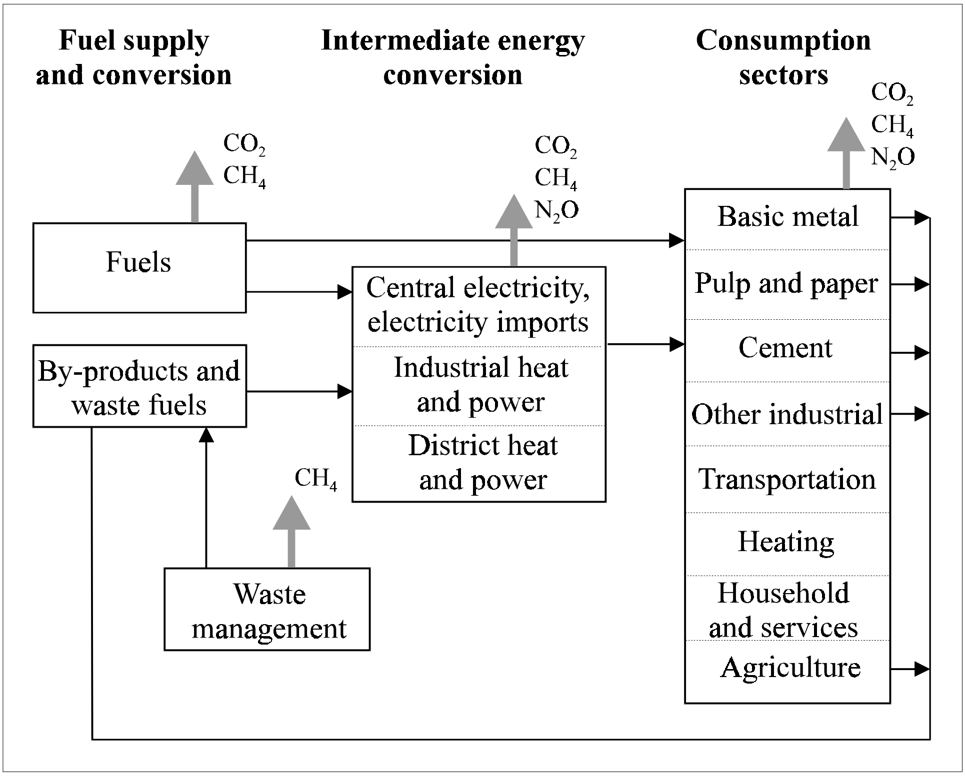

Figure 10. Overview of the modular structure of the EFOM model.

capacities) for the end of each sub-period. For practical computational reasons the number of subperiods in a large model is usually limited below 8. The solution of the model is obtained by global optimisation over the whole study period under consideration. Consequently, although the model can describe important dynamic properties of the energy system, there is no genuinely dynamic behavior in the model itself.

Due to national characteristics the Finnish EFOM model differs in many aspects from similar models that have been used for other countries. Some of the main differences are already reflected by the top-level model structure depicted in Figure 10. Significant additions to the model include the supply of domestic fuels, a considerably detailed pulp and paper subsystem, as well as feedbacks introduced between the industrial sectors and the supply of byproduct and waste fuels. Furthermore, the importance of CHP has required much more consideration for the cogeneration sectors than in the EFOM models of most other countries.

The inclusion of a relatively detailed description for agriculture and waste management has been a major recent extension to the model. Full modules for these sectors were added to the model in order to reach a sufficiently comprehensive representation of methane and nitrous oxide emissions and relevant measures for emission abatement. To improve the model description and the use of the model some modifications have been made also to the original EFOM software. The modifications support, for instance, flexible formulation of almost any additional equations considered necessary for the realistic behaviour of the model, and easier management of different scenarios.

As an energy system optimisation model the objective of the EFOM model is to determine the optimal use of resources in energy supply and conversion, and to some extent, in final energy demand. The system is optimised by linear programming using the total present value costs of the entire energy system over the whole study period as the objective function to be minimised.

Optimising the energy system with respect to the total present value costs complies with the idea that national resources should be used rationally for the total benefit of the national consumers. Using the global cost optimisation criterion can be viewed as simulating the behaviour of economic agents under the assumption of perfect competition and complete market information. Because in reality the markets are far from perfect, it does not reflect the actual behaviour realistically, but describes a possible target situation which might be approached by various legal standards and economic policy measures.

The optimisation criteria are also in accordance with the concept of least cost planning, which aims at measuring the energy supply technologies and the demand technologies by the same economic, technical, and environmental parameters. As in a true least cost solution, the model considers the supply and demand options together, taking into account potential energy savings alongside new power plants. However, the costs in an engineering-oriented model like EFOM address only direct energy-system costs. Transaction costs and other hidden costs or macroeconomic relationships (multiplier effects, structural effects and price effects on the useful energy demand) are difficult to incorporate in a traditional linear optimisation model for the energy system.

Perhaps the most important disadvantage of the model is that it does not address the interactions between the demand for energy services and the prices of energy. To a certain extent the price effects are captured by the introduction of energy conservation options, which decrease the final energy consumption when energy prices begin to escalate. More general economic effects, however, represent yet much more complex elasticity mechanisms between the economic activities and the demand for energy. Some models (e.g. MARKAL) incorporate a simple macroeconomic model, which can immediately be used to adjust the useful energy demand scenario of the optimisation model. Other models try to represent the interactions between demand and prices only within the energy intensive sectors, leaving other economic interactions out of consideration. Models using the latter approach are called partial equilibrium models.

Another drawback of linear optimisation models is generally the absence of regional aspects, which is caused by the need to keep the model size manageable. Furthermore, small variations in input parameters can sometimes lead to surprisingly large variations in the solution, and the most attractive technologies may dominate the solution even if the cost-differences are very small. Such unrealistically extreme characteristics of the solution can, however, be avoided by introducing additional constraints improving the correspondence with reality.

A central part of the model application is the definition of scenarios. The scenarios may include varying assumptions both about the characteristics and availability of different technologies and about policy measures such as energy taxes or constraints for the amounts of emissions or energy resources. The scenarios analysed in this study are described in Chapter 6.

5.2 The supply modules

The supply modules include the description of primary energy supply, fuel refining and conversion into electricity or heat. The description of the supply of fossil fuels is basically very simple. Scenarios have been defined for the prices of fuels supplied to the largest-size consumers at the most favourable sites, as well as for the costs of transportation and distribution to different consumer categories. Table 25 summarises the baseline price scenarios for the most important fuels.

Table 25. Baseline scenario for the prices of main fossil fuels to large-size consumers, excluding taxes.

FIM95 / GJ	1995	2000	2010	2020	2040
Steam coal, 1.5% S	7.2	8.3	8.4	8.6	9.4
Steam coal, 0.8% S	7.8	9.1	9.3	9.5	10.2
Heavy fuel oil, 2% S	13.3	17.4	20.1	21.8	24.6
Heavy fuel oil, 0.9% S	17.6	22.2	25.0	26.8	29.7
Light fuel oil	23.1	29.9	34.4	37.4	40.2
Natural gas [1]	13.6	14.9	17.2	18.9	21.4
Milled peat [2]	12.8	12.6	12.9	12.9	12.9

[1] Variable portion of the price for large-size consumers (49 FIM / MWh in 1995).

[2] Price for large-size CHP plants. Special rates are used for condensing plants at mires.

Regarding the supply of natural gas, the model includes a description of the domestic natural gas network. Investment costs have been estimated both for the main pipelines as well as for smaller distribution lines. Additionally, due to security of supply considerations, a storage requirement has been set if the dependency on natural gas is increased to a very high level in proportion to the total primary energy supply. As a baseline scenario, the level has been set to be 20% of total primary energy excluding transport fuels and electricity imports. When this level is exceeded, 25% of the amount in excess is required to be held in reserve storage. In more pessimistic scenarios yet stricter requirements have been applied for both the proportional requirements and reserve storage.

Estimates for the potential of biomass fuel supply were already presented in Section 4.1.1. The assumptions used in the present study are shown in more detail in Table 26. The potentials related to spent pulping liquors and by-product wood from the forest industries are fully determined by the model from the levels of activity in the module for forest industries.

Concerning recovery boilers, which represent the most important single technology in the industrial self-production of electricity, the model includes the possibility of increasing the average power to heat ratio in such plants up to 0.3 in full back-pressure mode by the year 2020, while at present the average ratio is about 0.2. Technically the increase in power production has been assessed to be quite feasible (Komulainen et al. 1994). Due to the high investment costs in relation to the gains in power and probable deficiencies in the self-sufficiency of

Table 26. The prices of non-byproduct biomass fuels (excluding waste), and the supply potentials assumed in 2010.

	Costs, FIM95 / GJ			**Potential in 2010, PJ**	
	1995	**baseline 2010**	**optimistic 2010**	**baseline**	**optimistic**
Residual wood fuels					
Cost category A	15.4	13.5	12.6	21.9	26.7
Cost category B	18.7	16.9	14.8	18.2	26.7
Cost category C	23.0	21.3	18.2	25.5	32.8
Cost category D	27.0	26.4	21.8	42.5	32.8
Total residual wood fuels				108.1	119.0
Firewood	32	32	32	57.5	57.5
Agrobiomass	17.7	15.4	15.4	5.0	5.0

fuels for process heat, as yet the pulp industries have utilised only a small part of this potential for increased power production.

In the modules for power and heat generation, all major plant types currently in use in Finland have been described. Additionally, for several plant types two different size classes have been included (e.g. CHP plants based on fluidised bed boilers or natural gas combined-cycle technology). The existing capacity stock at the end of 1997 has been fully taken into account, and major plants under construction in 1998 have been included as well. The classification of the existing stock is based on a database collected and maintained at VTT Energy. Estimates for the costs and technical performance of different plant types are based on a number of surveys (e.g. STYV 1992, Kosunen & Leino 1995).

The baseline assumptions used for selected advanced combustible fuel-based power and heat generation technologies are presented in Table 27, with data for a few conventional technologies given as a reference point. As indicated in the table, the investment (and O&M) costs for technologies still under major development are assumed to decrease in the future. In the case of separate electricity generation technologies, also the efficiencies are assumed to improve, while in the case of CHP technologies slow increases in the average power to heat ratios are assumed instead.

Table 27. Baseline assumptions for selected power and heat generation technologies.

			Time of commissioning			
			2000		2020	
Plant type	**Plant size MW(e)**	**MW(h)**	**Investment FIM / kWe**	**Net energy efficiency**	**Investment FIM / kWe**	**Net energy efficiency**
Separate power production						
Pulverized coal, conventional	500	0	5040	41.5%	5040	42.0%
Pulverized coal, advanced	500	0	5400	44.0%	5400	46.0%
IGCC, coal	250	0	7490	46.0%	6587	49.5%
PFBC, coal	250	0	7070	44.0%	6217	46.0%
NGCC	200	0	3310	51.0%	3310	55.0%
Diesel engine, gas	95	0	3850	47.0%	3850	50.0%
Gas engine, biogas	1	0	5500	38.0%	5500	39.0%
District heat and power						
AFBC, coal	90	160	7020	86.0%	7020	(*)
AFBC, biomass	30	60	9170	82.0%	9170	(*)
IGCC, coal	90	90	8880	86.0%	7809	(*)
IGCC, biomass	60	60	9990	84.5%	8785	(*)
IGCC, biomass	40	40	10840	84.5%	9533	(*)
PFBC, coal	90	126	9260	86.0%	8143	(*)
PFBC, peat	50	70	10410	86.0%	9155	(*)
NGCC, gas	160	160	3930	90.0%	3930	(*)
NGCC, gas	60	60	5000	88.0%	5000	(*)
GT, WHB, gas	40	70	4260	90.0%	4260	(*)
GT, WHB, gas	16	28	5130	88.0%	5130	(*)
Diesel engine, gas	46	46	4400	88.0%	4400	90.0%
Gas engine, biogas	1	1.5	5940	90.0%	5940	(*)
Fuel cell	15	5	16460	90.0%	7290	(*)
Industrial CHP						
AFBC, coal	45	130	8670	87.5%	8670	(*)
AFBC, wood biomass	16	52	10220	84.5%	10220	(*)
IGCC, wood biomass/peat	57	70	10830	85.0%	9429	(*)
IGCC, wood biomass	30	37	12340	85.0%	10744	(*)
IGCC, pulping liquors	80	120	12290	82.0%	10830	(*)
IGCC, pulping liquors	50	75	13510	82.0%	11905	(*)
NGCC	71	89	4570	89.5%	4570	(*)
GT, WHB, gas	40	70	4260	88.5%	4260	(*)
Diesel engine, gas	15	17	5030	90.5%	5030	(*)

*) Total energy efficiency assumed to remain constant, but instead a gradual increase in power to heat ratio is assumed, typically about 5% by the year 2020.

Regarding wind and solar power, the baseline assumptions for investment costs are illustrated in Figure 11. The assumed decrease in costs for wind power (about 20% by the year 2020) is slightly smaller than in several other estimates published. The baseline estimate for the potentials of wind power on land and offshore are in line with the discussion and estimates given in Section 4.1.1

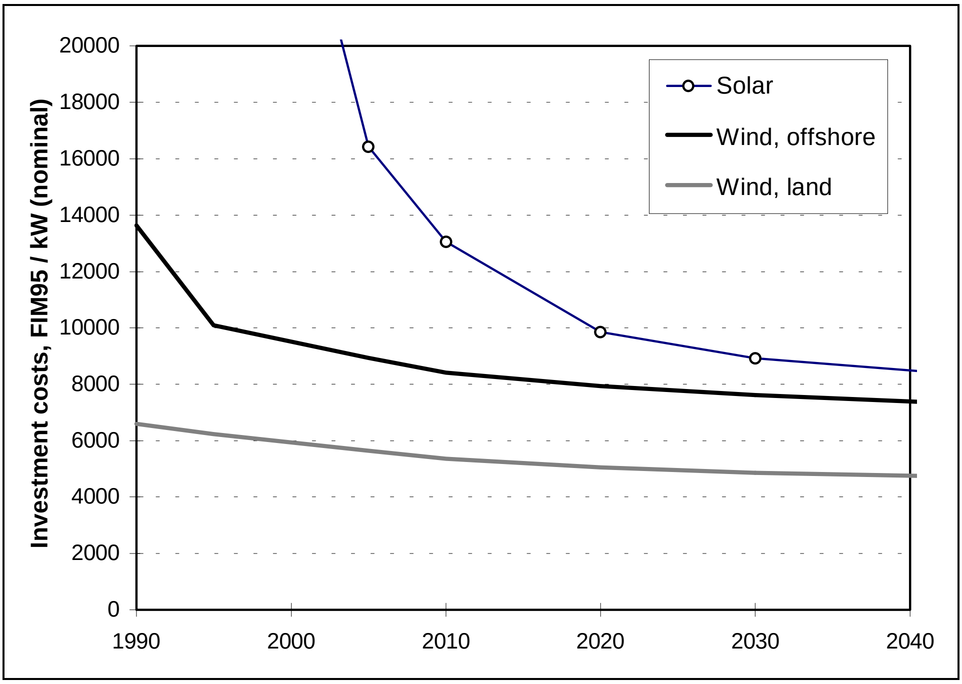

Figure 11. Baseline assumptions for the investment costs of wind and solar power.

The representation of the penetration of some new technologies has been additionally enhanced by using a simplified endogenised learning mechanism. Because of being still more or less experimental in this study, the mechanism was implemented only for CHP fuel-cells and for the integrated gasification of spent pulping liquors. The methodology is a refinement to the rather rigid scheme that was originally included in the EFOM software. It is based on the assumption that the investments in commercial plants may occur only after initial investments in demonstration plants, but may thereafter increase exponentially with increased experience in production. The investment costs of the demonstration plants are assumed to be considerably higher than those on a commercial scale.

Although the learning mechanism is rather simplified, it is useful because it inhibits postponing all investments in new technologies until their costs are assumed to have become low enough. While such an opportunistic strategy could well be feasible with small-scale consumer technologies developed elsewhere, in the case of energy technologies considerable experience from local applications is normally required.

5.3 The demand modules

5.3.1 Manufacturing sectors

The Finnish EFOM model contains an exceptionally detailed description of energy-intensive industrial sectors compared to most other models of similar type. The motivation for the detailed representation has been the very important role of manufacturing industries in the Finnish energy economy. The most energy-intensive sectors are forest products industries, basic metals manufacturing, and chemical industries. Of these, both the forest industries and the production of basic metals are described on the level of identifiable product categories.

Chemical industries include such diverse production processes that in the present model version the structural description is made on the level of value added only, which is taken to be the driving demand of the sector. The same approach is used also for the remaining industrial sectors. Additionally, crude sub-sectoral analyses based on value added have been performed for all the industrial sectors described. The development of specific consumption for electricity, process heat and direct fuel uses have been estimated for all the sub-sectors considered, largely on the basis of historical data from Statistics Finland (e.g. Statistics Finland 1996).

In pulp and paper manufacturing the model distinguishes between 13 classes of pulp qualities (of which some are obsolete, however), 11 classes of paper or board qualities, and an aggregated description for the production of further refined paper products. All production processes have been assigned with estimated specific consumption of electricity, process heat, and direct fuel uses. On the aggregate level the representation is found to cover fully and sufficiently accurately the total energy consumption in the sector. A separate, yet more detailed stand-alone model has been used as a basis for the description (Tamminen & Forsström 1991). The various products and processes have been described in more detail in an earlier report (Lehtilä 1995).

The development of the structure of pulp and paper manufacturing has a large impact on the total energy consumption. In the present study, no room has been left for the optimisation of the product structure on the basis of, for instance, value added. The projection for the future structure is mostly based on a recent survey carried out in the Sustainable Paper research programme (Carlson & Heikkinen 1998). Figure 12 illustrates the scenario derived for the mix of raw-materials used in paper and board production. The demand scenario is presented in Section 6.2.2.

Product- and process-level specific consumption of electricity and heat has in most cases been assumed to be slowly decreasing in the future. For electricity, the average decrease has usually been assumed to be 0.2% per annum for electricity, and 0.5% per annum for process heat. A notable exception is mechanical pulp production, where the trend of increasing specific consumption of electricity is expected to be continued due to requirements for finer qualities.

In the basic metals manufacturing the model description includes the production processes for pig-iron, basic oxygen furnace steel, electric steel, ferrochrome, stainless steel, hot rolling and cold rolling of steel, iron casting, copper, zinc, nickel and secondary aluminium. Coking plants are also described, but are included in the module for solid fuel supply. Baseline projections for production volumes are based on the scenarios of MTI (MTI 1997a), as well as on other surveys (e.g. TELI 1995, Mäenpää et al. 1996). With few exceptions, the

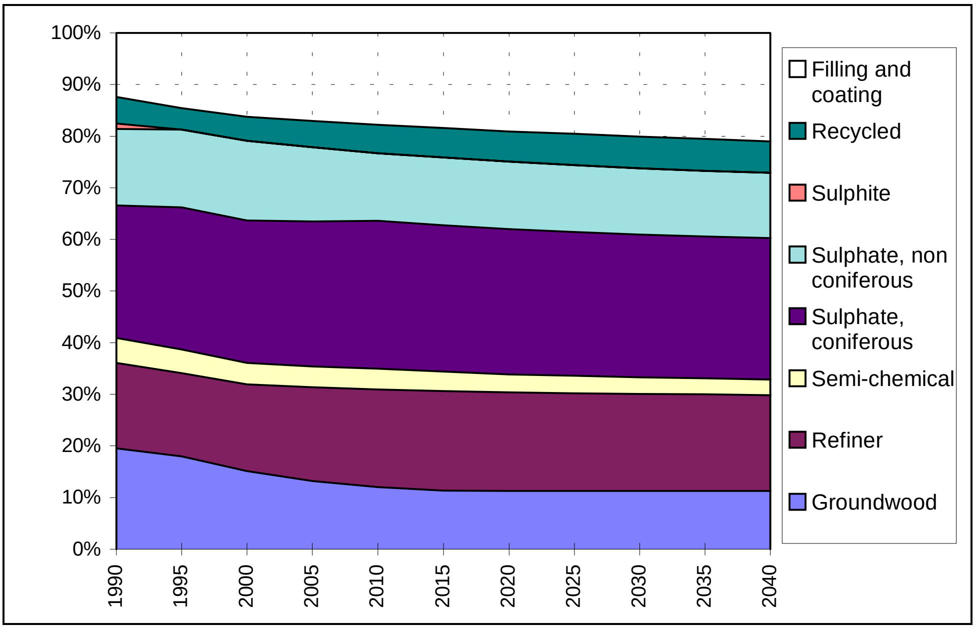

Figure 12. Raw-material mix assummed for paper and board production.

autonomous changes in specific consumption have been assumed to be quite small. Compared to pulp and paper production, the average annual decrease in specific electricity consumption has, in general, been assumed slightly larger, between 0.2% and 0.4%. Exceptions are cases where ongoing or planned modifications to the production processes are expected to bring about notable changes in energy consumption.

As the product mixes have been to a large extent fixed in the present study, the primary means for affecting the intensity of energy use is energy conservation. As indicated in Section 4.1.2, the potential for energy saving has been estimated on the basis of various Finnish studies. The costs, on the other hand, are not directly based on any of the surveys. According to many studies there exists considerable potential for energy conservation measures that cost less than the cost of the saved energy (so-called no-regret or win-win situations). In the present study, however, assumptions of such potentials were considered to produce unrealistic results. Therefore, the costs of all conservation measures

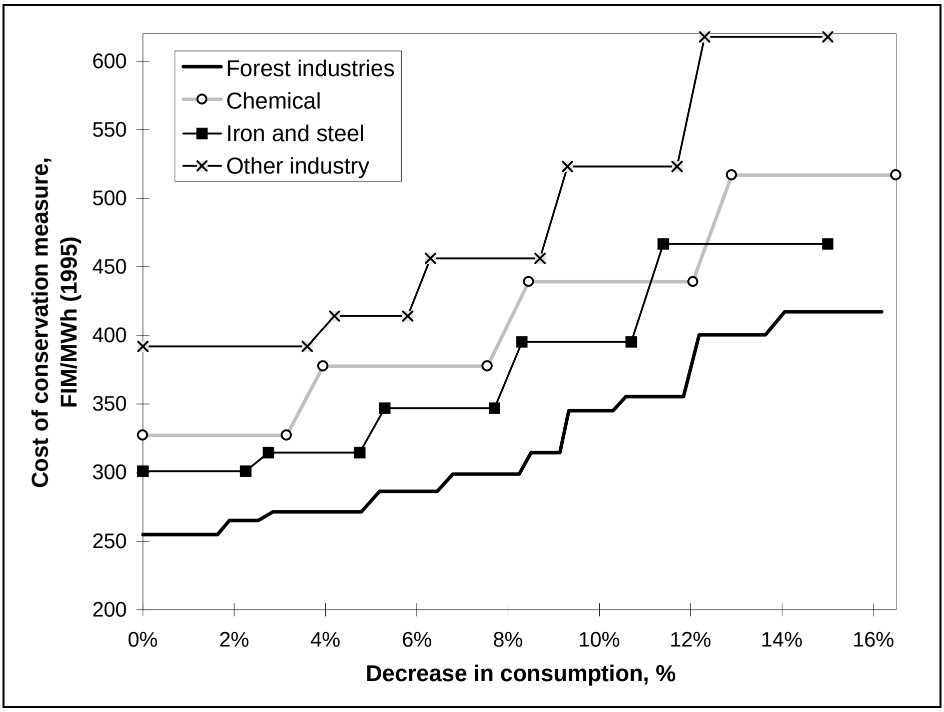

Figure 13. Cost curves used for the measures to decrese the intensity of electricity use in manufacturing sectors.

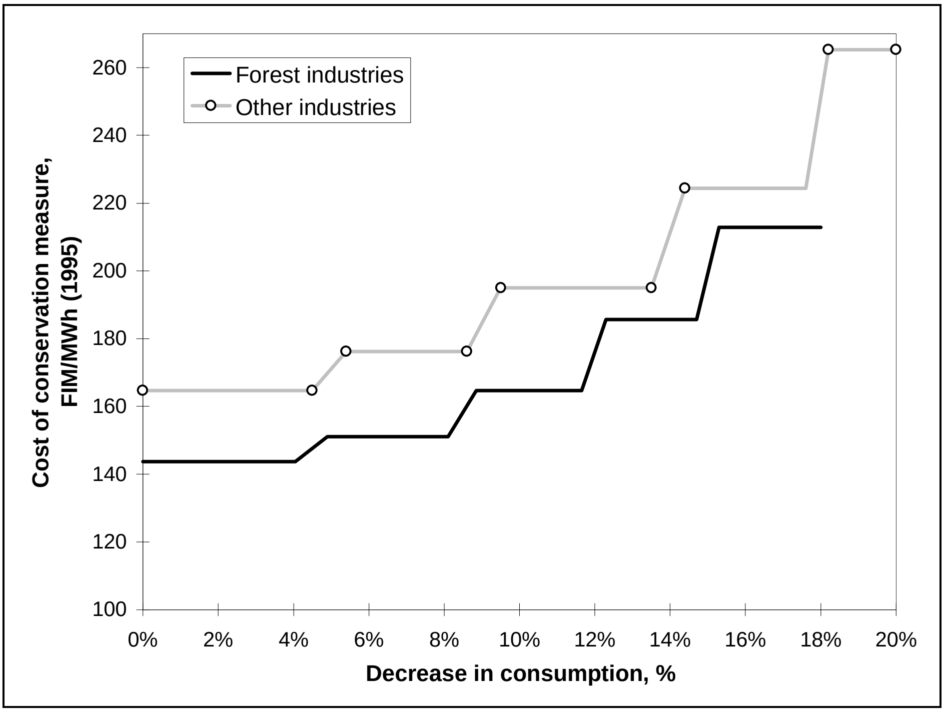

Figure 14. Cost curves used for the measures to decrese the intensity of process heat consumption in manufacturing sectors.

were calibrated against the baseline scenario in such a way that no measures will become profitable in the baseline scenario. Nevertheless, an attempt was made to preserve the shape of the cost curve for each sector as estimated from the original data sources. Cost curves for the energy conservation measures in the industrial sectors are illustrated in Figures 13 and 14.

5.3.2 Residential, tertiary and transport sectors

In the module for residential and tertiary energy use, the technical options for space heating have been described in considerable detail. The module includes all major types of heating systems separately for single-family houses, multi-family houses, as well as for public and commercial buildings. Baseline projections for the market shares of different heating systems are based on a recent baseline scenario presented by the Ministry of Trade and Industry (MTI 1997a). The technical performance and specific heat consumption have been calibrated to be consistent with the actual data in 1995.

The assumptions about the autonomous improvements in the thermal integrity of buildings and efficiencies of heating systems are similar to those used by MTI (MTI 1997a). Accordingly, the average specific heat consumption is decreased by about 10% by 2010, and by about 15% by 2025. Additional improvements can then be achieved through explicit conservation measures. In the same way a baseline scenario has been defined for the consumption of electricity in households, in the commercial and institutional sectors, and in agriculture and construction.

Some of the most important baseline assumptions for the explicit conservation measures are listed in Table 28. The potentials are not assumed to be fully available until in 2015, but before that they are assumed to increase linearly. By-product heat from the consumption of electricity for lighting and appliances has been taken into account in the model. It has been assumed that 10–50% of the electricity consumption can be utilised as heat in the buildings, depending on the type of end-use. Consequently, a decrease in the electricity consumption of household appliances will increase the need for space heat production.

Potentially important technical options in the model for reducing the greenhouse gases from space heating include ground heat pumps and solar heating systems in single-family houses, and exhaust-air heat pumps in multi-family houses and service buildings. The estimates used for the costs of heat pump and solar systems are in line with the estimates presented in Section 4.1.3. The potential for heat pumps in single-family houses has been assumed to be about 5 % in 2010 and about 10 % in 2040. Similar maximum market shares have been assumed for service buildings, but only half of that in multi-family houses. However, as a baseline scenario the combined share of all heat pump technologies has been constrained to be at most about 2 % of the total heating of buildings in 2010, and at most 3 % in 2040.. In an optimistic case, this constraint has been relaxed to about 5 % in 2010 and about 8 % in 2040. The maximum potential for solar heating has been set at 0.7 TWh in 2010, and at 3 TWh in 2040.

The module for transport includes sub-modules for passenger and goods transport. The transport technologies described for passenger transport include gasoline cars (with or without catalytic converters), diesel cars, as well as electric, methanol, LPG and CNG (compressed natural gas) cars. For public

Table 28. Baseline scenario assumptions for the potentials and costs (1995 price level) of energy conservation measures in the residential and services sectors.

Consumption of heat in buildings

	Single-family houses		**Multi-family houses**		**Service buildings**	
	Potential %	Marg. cost, FIM/MWh	Potential %	Marg. cost, FIM/MWh	Potential %	Marg. cost, FIM/MWh
Measure 1	6%	480	6%	275	6%	315
Measure 2	6.5%	505	7%	290	6%	330
Measure 3	6.5%	545	7%	320	7%	350
Measure 4	6%	580	–	–	7%	380
Total	25%	580	20%	–	26%	380

Consumption of electricity in household and services

	Households		**Services**	
	Potential %	Marg. cost, FIM/MWh	Potential %	Marg. cost, FIM/MWh
Electric cooking	4.5%	370	1.5%	410
Cold storage 1	4.5%	350	2.5%	380
Cold storage 2	7.5%	445	–	–
Washing & cleansing	8.2%	410	6.9%	480
Misc. appliances	2.3%	375	5.0%	340
Lighting 1	7.0%	350	6.0%	330
Lighting 2	3.0%	465	5.0%	415
Lighting 3	–	–	5.0%	500
Total	37%		32%	

passenger transport the model includes buses, rail, and air transport. Goods transport based on gasoline or diesel vans, trucks, ships or rail are considered.

Because it would be very speculative to optimise the structure of transport by mode, the markets shares of different modes have been defined quite rigidly for the whole period considered, allowing only small deviations from a baseline projection. Therefore, the share of public transport cannot be much increased from the baseline in the model results even if that would be a cost-effective technical measure for emissions abatement. The baseline projections for the market shares are based on estimates produced by the LIPASTO model (Mäkelä et al. 1996, Mäkelä et al. 1997), and on a futures study made by the Ministry of

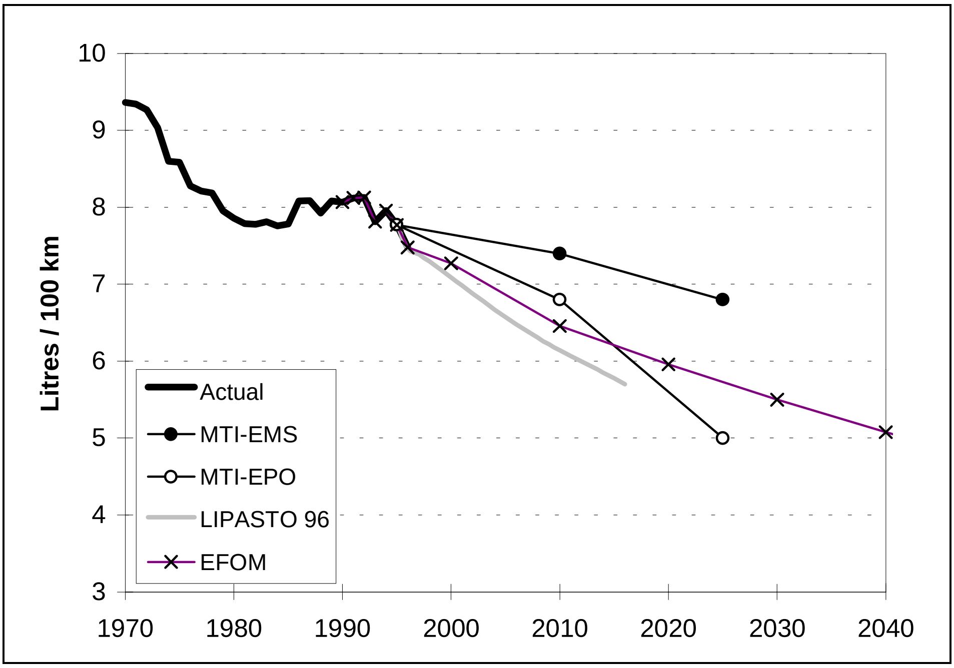

Figure 15. Actual development and assumptions used for the future fuel economy of private gasoline cars in the EFOM *model, and some other estimates.*

Transport and Communications (MoTC 1998). The projections for the fuel efficiencies of conventional transport vehicles are also largely based on the LIPASTO estimates, but with slightly smaller efficiency improvements (see Figure 15). Relatively large efficiency improvements were considered appropriate even in the baseline projection, as the model includes only few explicit measures, and only a small and expensive potential to reduce fuel consumption.

As to the new technologies, the costs estimates for methanol, LPG and CNG cars relative to gasoline cars are based on rather old German data (Ruß et al. 1991). The investment costs for electric cars have been assumed to be at present 40% higher than the costs for new gasoline cars. However, as a baseline assumption the costs are assumed to be slowly decreasing so that they become 23% higher than gasoline cars in 2030. In the optimistic cases the costs are reduced to a level of only 12% higher than gasoline cars in 2030. The technical performance of electric cars is based on a survey made in the early 1990s (Alppivuori & Himanen 1991). The cold winter in Finland has been taken into account by assuming small oil heaters in electric cars. The description of electric vans is similar in relation to gasoline vans as the description of electric cars is in relation to gasoline cars. In the year 2010 the market share of electric cars is assumed to be at most 5%, and that of electric vans 8%. In the year 2030 the corresponding maximum market shares have been set at 12% and 17%. In the optimistic scenario, however, the maximum market share of electric cars is assumed to be almost twice as high.

A few small energy conservation options are also included in the transport module. As in other sectors, the costs of the conservation measures have been calibrated to be notably higher than the saving in fuel costs. Consequently, the measures are assumed to be considerably more costly than what have been estimated, for instance, in the Energy conservation study (Lepistö 1991).

5.4 Modules for agriculture and waste management

The material flows in the waste management and agricultural systems are described in quite aggregated level in order to keep the total size of the EFOM model reasonable. The waste management module includes the flows of municipal and industrial solid wastes and sludges, and construction and demolition wastes. The management of municipal solid waste (MSW) has been described in more detail than the management of other waste categories, because the utilisation of the most significant industrial wastes and by-products, such as pulping liquors, has already been included in other modules. In the waste management module only landfilling of other waste categories has been described. The scenarios for the total amount of MSW and the landfilled amounts of other waste categories are presented in Table 29.

A scenario for the total amount of MSW has been calculated with help of population (MTI 1997a) and the factor for MSW generation rate in Finland (IPCC 1997), which is 1.7 kg/capita/day. According to this scenario the total amount of MSW is 3.1 Tg in 1990, and it remains quite steady over the whole period. The landfilled amount of other waste categories has been estimated with help of National disposal site register (Rytkönen 1997) and a scenario based on Ministry of the Environment (1997, p. 21).

Table 29. The scenarios for the total amount of MSW and other landfilled waste categories.

Tg/a	**1990**	**1995**	**2005**	**2025**	**2040**
Total amount of MSW	3.1	3.18	3.24	3.2	3.2
Other wastes to landfills:					
Industrial solid waste	0.63	0.63	1.2	1.2	1.2
Liquid industrial sludge	0.15	0.09	0.08	0.07	0.07
Dried industrial sludge	0.33	0.17	0.15	0.1	0.1
Liquid municipal sludge	0.23	0.15	0.12	0.12	0.12
Dried municipal sludge	0.3	0.25	0.2	0.2	0.2
Construction and demolition waste	0.36	0.32	0.2	0.2	0.2

The flow of municipal solid waste is divided in different waste fractions described in Section 2.3.2. The flows of these fractions to landfills can be reduced with different measures described in Section 4.2. Recovery of paper and board is directly linked to the pulp and paper module, and the utilisation of so-called "energy waste" is linked to the solid fuel supply module. The waste flows to landfills are converted to degradable organic carbon (DOC) with factors presented in Section 2.3.2. In landfills, which are bisected to small and big ones, the landfill gas due to wastes can be recovered and possibly utilised as told in Section 4.2.2. The landfill gas recovery and the anaerobic treatment of organic waste and manure are linked to the gas supply module.

In agricultural module the scenarios needed are the numbers of domestic animals, production of crops, the amount of synthetic fertilisers applied to land and the total area of peatlands in agricultural use. These scenarios are presented

Table 30. The scenarios for the numbers of domestic animals (thousands).

Animal category	**1990**	**1995**	**2000**	**2005**	**2010**	**2040**
Dairy cattle	489.9	398.7	363.0	343.0	343.0	343.0
Other cattle	869.8	749.4	653.0	617.0	617.0	617.0
Swine	1,381.4	1,400.3	1,400.0	1,400.0	1,400.0	1,400.0
Sheep	103.3	158.6	130.0	130.0	130.0	130.0
Horses	43.9	49.5	50.0	50.0	50.0	50.0
Poultry	4,844.8	4,175.1	3,875.0	3,690.0	3,690.0	3,690.0

Table 31. The scenarios for crop production, utilisation of fertilisers, and the total area of peatlands in agricultural use.

	1990	**1995**	**2025**	**2040**
Crop production (kt/a)	4 296	3 333	2 500	2 500
Fertilising (kt (N)/a)	228	295	165	165
Peatlands (km^2)	2 000	2 000	2 000	2 000

in Table 30 and in Table 31. The CH_4 emissions from digestion and the N_2O emissions from manure are calculated directly from figures in Table 30, which are later in the module converted to material flows of manure. The CH_4 emissions from manure management are calculated with the help of these flows, and they can be reduced with measures described in Section 4.2. The N_2O emissions from synthetic fertilisers, crop residues left in the fields, and peatlands are calculated with data in Table 31 and emission factors described in Section 2.4.3.

The numbers of domestic animals and the amount of synthetic fertiliser applied to the land have been taken from Ministry of the Environment (1997, p. 21). The present production of crops has been adapted from FAO database (FAOSTAT 1997), and the total area of peatlands is assumed to remain constant (200,000 hectares) over the whole period.

A couple of new industrial greenhouse gas emission sources have also been added into EFOM: nitric acid production and the manufacturing of lime. Estimated production scenarios used in this study are presented in Table 32. Values for past production have been taken from Statistics Finland (1993, 1995). It has been assumed that the production of both nitric acid and lime will decrease in the future, because agricultural activities will probably be reduced. As possible future increases in the use of metallurgical lime were not considered in the scenario, this assumption may lead to a slight underestimation of the total production of lime. The N_2O emissions from nitric acid production can be reduced with catalysts as stated in Section 4.3.2.

Table 32. The scenarios for lime and nitric acid production (kt/a).

	1990	**1993**	**2010**	**2025**	**2040**
Lime production	413	378	350	300	300
Nitric acid production	551	461	400	350	350

6. Scenarios

6.1 Overview

The purpose of the scenarios analysed in the study is to identify cost-effective measures for greenhouse gas abatement in Finland. As the possibilities for utilising various technical options are in many cases still quite uncertain, different scenario assumptions have been used for selected groups of options. In all the scenarios considered the time scale is from 1990 to 2040.

In this study, five different basic scenario alternatives have been considered. Within one scenario, both reference and 1–3 reduction cases have been examined. In the reference cases no reduction objectives are applied. In the reduction cases a target is set either for the total greenhouse gas emissions expressed in CO_2-equivalents, to CO_2 emissions only, or for the radiative forcing (RF) due to emissions. The reduction objectives are considered in detail in Section 6.3.

The main purpose of the alternative scenarios is to study the potential effects of different technical options which could have importance in CO_2 abatement in the energy sector. The alternative assumptions considered for the options are related to the following parameters:

- Maximum imports of natural gas
- The costs of biomass supply and its new utilisation techniques
- The costs of other new energy technologies
- The costs of energy conservation measures.

Table 33 summarises the differences in the main assumptions of the basic scenario alternatives. The first scenario (Gas 17%) is the most pessimistic one. It describes the situation, where the utilisation possibilities of emission reduction options will basically remain at the present level. The level of optimism concerning various emission reduction options is gradually increased in the subsequent scenarios. In the Gas 20% scenario the supply of natural gas is assumed to be more secure and therefore the imports may be increased to a higher level with lower costs than in the first scenario. In this case a new natural

Table 33. Summary of the scenarios.

Option	*Gas 17%*	*Gas 20%*	*Biomass*	*Newtech*	*Save*
Secure level of natural gas supply [1]	17%	20%	20%	20%	20%
Costs of biomass fuels and technologies	higher	higher	lower	lower	lower
Wind power potential	small	small	small	large	large
Costs of other new technologies	higher	higher	higher	lower	lower
Costs for energy conservation measures	higher	higher	higher	higher	lower
Reduction objectives	GHG	GHG, CO_2, RF	GHG	GHG	GHG, CO_2

gas pipeline connection to western Europe would be required. The effects of lower-cost biomass utilisation, new technologies, and energy conservation measures are considered in scenarios Biomass, Newtech, and Save, respectively.

All emission reduction objectives are studied only in the Gas 20% scenario in order to keep the total number of the calculation cases reasonable. Gas 20% is also considered as the base scenario. In the Gas 17% scenario the assumption for the upper bound of natural gas imports is quite conservative, and therefore it has not been chosen as the base scenario. CO_2 reduction is also examined in the Save scenario in order to establish the significance of the CH_4 and N_2O emissions under the most optimistic projections.

Assumptions concerning the general development of the economy are, of course, crucial for the scenario results. The growth in economic activity is directly reflected in the demand for energy services. As the EFOM model is driven by the demand for useful or final energy (products, useful heat, etc.) in the consumption sectors (Lehtilä & Pirilä 1996), the demand scenarios must be given exogenously. In this study only a single scenario is used for the

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[1] Max. imports of natural gas is expressed as a fraction of the total primary energy consumption excluding electricity imports and transport fuels.

development of activity levels in end-use sectors. Consequently, the demand for useful energy is assumed to be the same in all scenarios. An effort has been made to construct the demand scenarios in such a way that they would correspond well to recent developments and projections. The scenarios are basically in accordance with the Energy Market Scenario (EMS) of the Ministry of Trade and Industry, which is the latest official baseline scenario in Finland (MTI 1997a).

6.2 Demand scenarios

6.2.1 Overview

Basic characteristics of the baseline scenario in terms of relations between GDP, total primary energy consumption (TPES), and total electricity consumption (TES) are illustrated in Figure 16. The overall energy intensity of the Finnish economy, as measured by the ratio of total primary energy consumption to GDP,

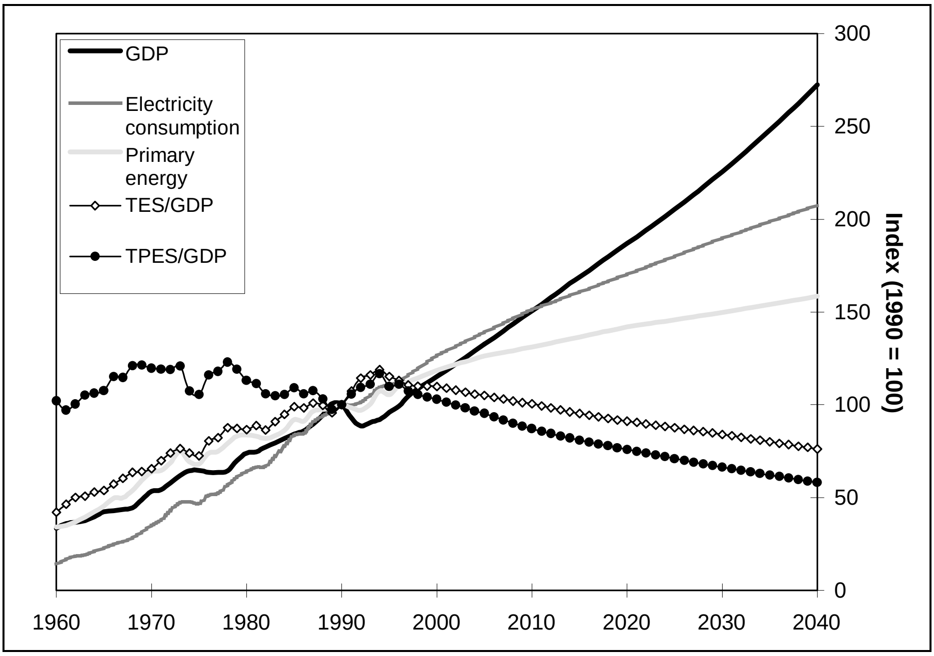

Figure 16. Development of GDP, total primary energy consumption, and the ratio of total primary energy and electricity consumption to GDP in the baseline scenario.

is expected to continuously decrease in the future. Also, the ratio of total electricity consumption to GDP started to follow a downward trend in 1994, and this trend is expected to be permanent.

In all end-use sectors the demand scenarios describe the development of the level of activity in the different uses of energy services. For each end-use category, the final demand for energy (specific electricity, heat, or fuels) is determined by the model in two stages. First, the non-price-induced final energy demand is computed by multiplying the projected specific energy consumption by the activity level. In the second stage, explicit price-induced energy conservation measures can be introduced to decrease the actual final energy demand.

The main baseline assumptions concerning the cost curves of energy conservation measures in each sector were described in Section 5.3. In general, the baseline costs are considerably higher than those estimated in other studies using a relatively low requirement for the rate of return. The baseline thus corresponds to the realistic assumption that due to the risks involved and practical barriers for implementation, the actual costs of the measures are higher than could ideally be estimated.

The Save scenario represents the possibility that the actual costs of the energy conservation measures could be somewhat closer to the estimates based on low-risk investment calculations. Nevertheless, even in this case the costs have been kept at a level high enough to prevent the measures from entering the solution of the reference scenario. In general, the costs are in the optimistic case 15% lower than the baseline costs. However, in the case of measures to improve the thermal integrity of buildings, or to reduce the fuel consumption of vehicles, the costs are assumed to be only about 10% lower compared to the baseline.

6.2.2 Manufacturing

The baseline scenario of MTI has been used as the main starting point for the manufacturing scenarios. However, as the growth in output of several manufacturing industries accelerated during the second half of the 1990s, the projections made by MTI in 1997 (MTI 1997a) have been slightly revised upwards for some branches, particularly for the metal products industries.

Forest industries

Within the EFOM module for forest industries, the demand of useful energy services can be expressed in amounts of end-products produced. The projection for the quantities produced in forest industries is partly based on the MTI scenario and partly on more recent studies. A study made under the Sustainable Paper research programme (Carlson & Heikkinen 1998), and another study made by the Finnish Energy Industries Federation (Finergy 1997) have both indicated that growth in the output of the pulp and paper industries by the year 2010 is expected to be considerably lower than was assumed in the MTI scenarios. These new estimates have been taken into account in the baseline scenario. Until about 2010 the production scenario is primarily based on the projection made in the Sustainable Paper programme.

Figure 17 illustrates the demand scenario for the production of pulp and paper. The total production in 2005 would be 14.4 Tg, which is 3% higher than the

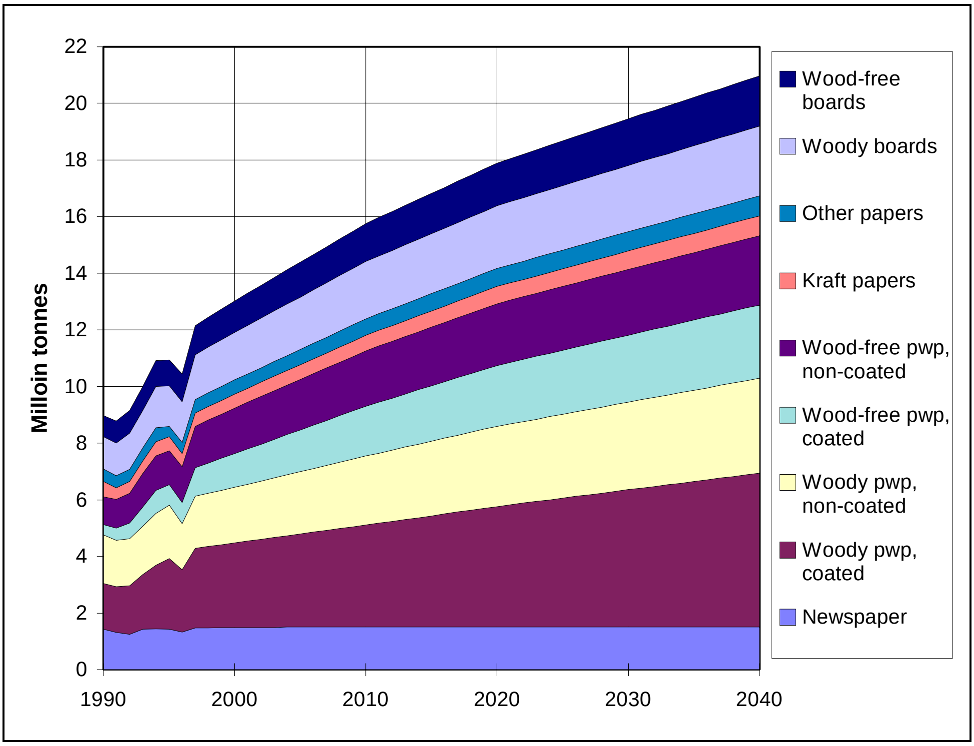

Figure 17. Scenario assumptions for the demand of paper and board.

projection of Carlson & Heikkinen (1998). In the mechanical wood processing industries the growth in production volumes has been assumed to be smaller than in pulp and paper manufacturing.

From the demand scenarios, the model determines the consumption of electricity, process heat and so-called direct fuels by using the scenarios defined for specific energy consumption. As was already mentioned in Section 5.3.1, the specific electricity consumption in the pulp and paper manufacturing processes was assumed to be decreased by 0.2% per annum, on average. When looking at the energy consumption in proportion to value added instead of the average product-level specific consumption, the decrease in energy intensity is somewhat larger. This is shown by the figures in Appendix B, which presents the demand scenarios for each manufacturing sector in terms of value added and by showing the trends in electricity and process heat consumption per value added.

Basic metals

As in the case of forest industries, the demand scenario for basic metals consists of estimates for the amounts of products produced. The scenario for ferrous metals is in line with the MTI scenario (MTI 1997a). As to the non-ferrous metals, the growth in the production of zinc and copper is assumed to be somewhat lower than the estimates published by the industry in 1995 (TELI 1995). However, up to the year 2010 the scenario should be well in accordance with most recent projections. The production scenarios are shown in Figures 18 and 19 Appendix B presents the corresponding scenarios for the value added in basic metals manufacturing and the intensities of electricity and heat consumption on the basis of value added.

Chemical industries

In the case of chemical industries, the demand for useful energy is defined to be the value added. This is due to the products and production processes being so diverse that reasonable benefits from a detailed process-level description could not be obtained without increasing the size of the model considerably. The scenarios for the value added and the trends in the intensities of electricity and process heat consumption are presented in Appendix B by sub-sector.

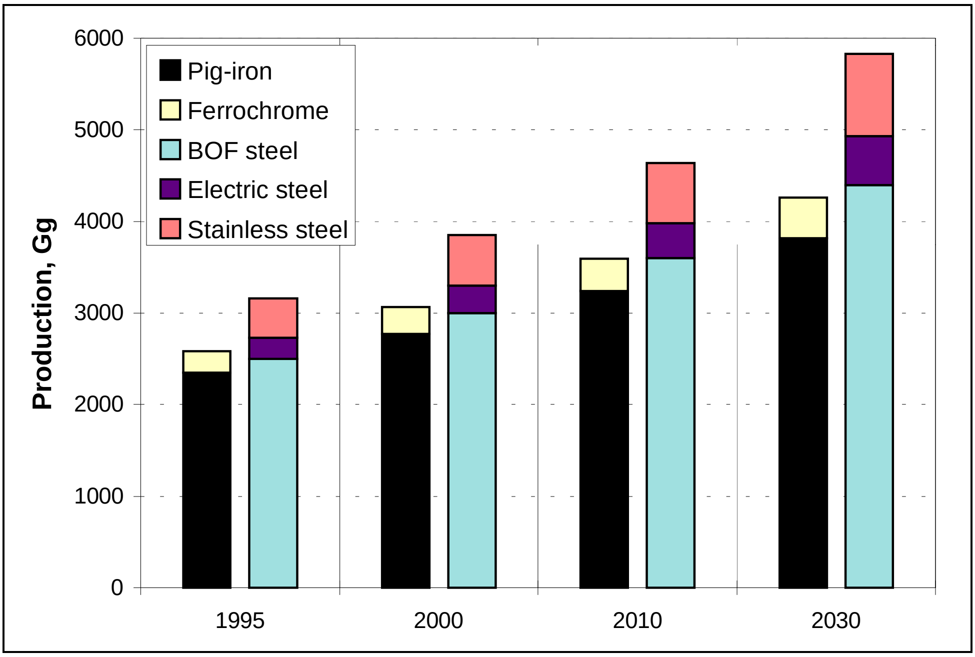

Figure 18. Scenario assumptions for the production of ferrous metals.

Non-metallic minerals

The EFOM module for non-metallic minerals production includes a process-level description for cement and lime manufacturing. The production of burnt lime in the future was, in this study, assumed to remain approximately at the present level, while cement manufacturing was assumed to notably increase after the drop in output during the first half of the 1990s. For the lime production the scenario has since turned out to be probably too low, as information about recent and future capacity expansion has become available. Consequently, the process emissions from lime production may be somewhat underestimated, but the misjudged projection will have only a small overall impact on the results. The remaining branches of non-metallic minerals manufacturing are described on the level of value added. The scenarios for the value added and the trends in the energy intensities are presented in Appendix B by sub-sector.

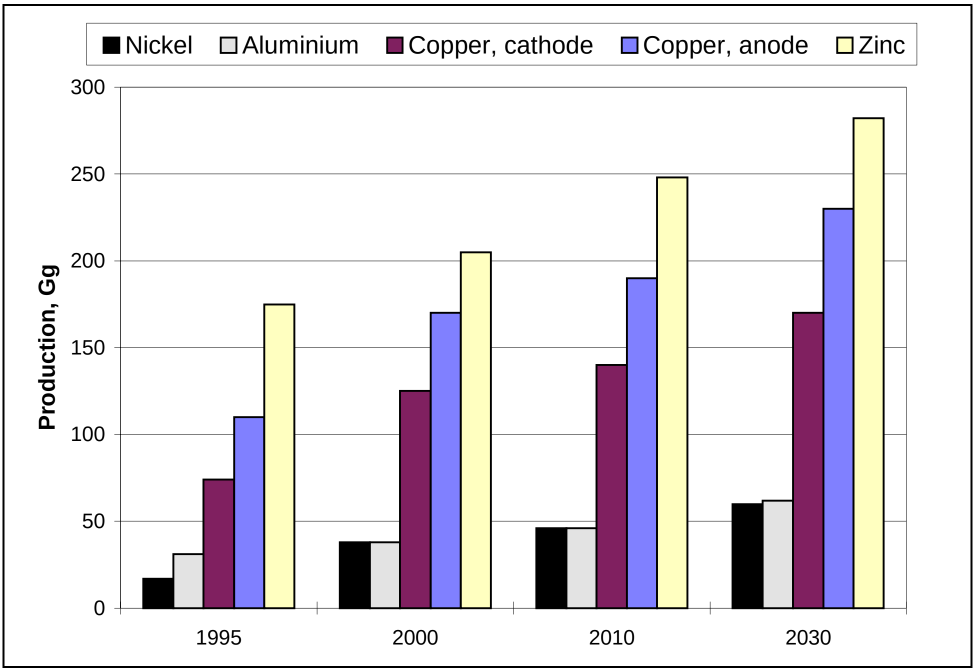

Figure 19. Scenario assumptions for the production of non-ferrous metals.

Other industries

In a similar way to the chemical industries, the demand in all other industrial branches is described by scenarios for value added. The assumptions on economic activity and intensities of electricity and heat consumption are illustrated by the Figures of Appendix B.

6.2.3 Residential and tertiary sectors

The driving demand in the residential sector is taken to be the volume of residential buildings for space heating, population for water heating, and the number of households for cooking and specific electricity uses. None of the components of energy consumption is directly proportional to the corresponding demand level, but for various reasons the energy intensities change over time. An attempt has been made to take into account all significant factors affecting the specific energy consumption per unit of each demand component.

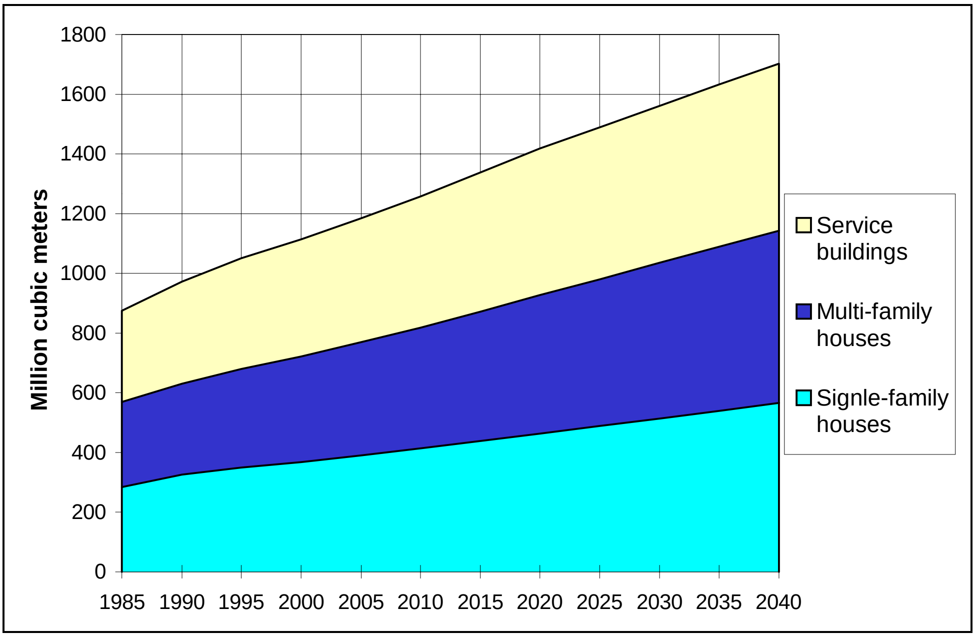

Figure 20. Scenario for the development of the building stock.

The scenario for building volumes is presented in Figure 20. Apart from the volumes, other factors affecting the demand for space heat include autonomous and explicit efficiency improvements, and electricity use in appliances. The baseline scenario for specific electricity uses in households includes the consumption for cooking, lightning and appliances. The scenario is mainly based on historical development of electricity consumption in relation to the average size of households, GDP growth, and the technical development assumed. Relations between population, number of households, household electricity and GDP are shown in Figure 21.

The scenario for the commercial and institutional (service) sector is based on the assumed growth in value added and the building volume in this sector, as well as on the expected technical upgrading of the appliance stock. The scenarios for agriculture and construction are based on similar considerations. Figure 22 presents the resulting baseline scenarios for value added and electricity consumption in the service sector.

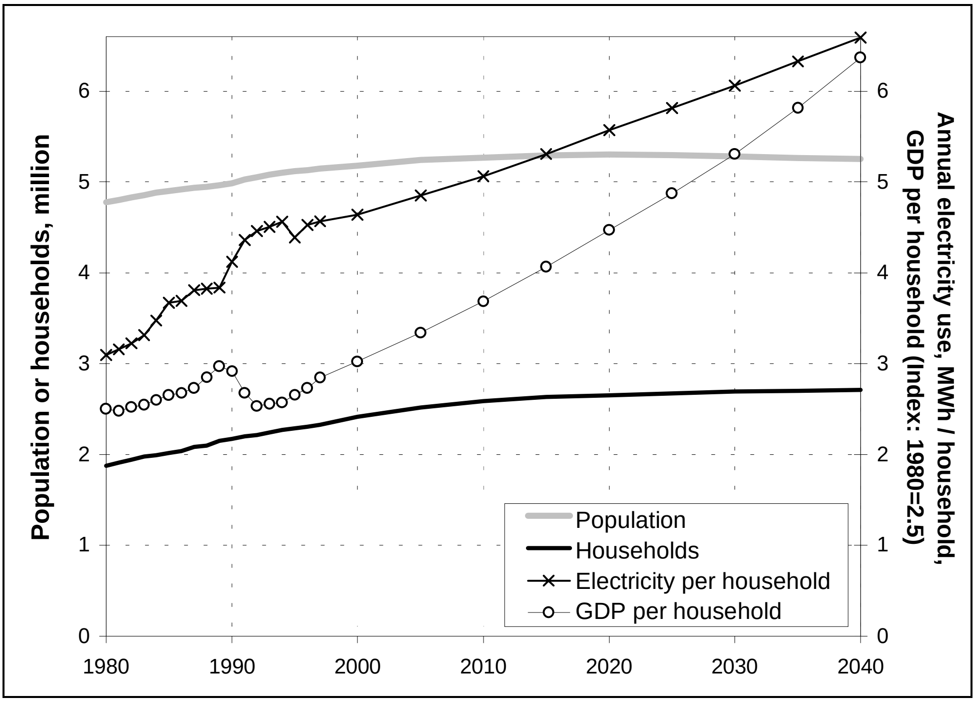

Figure 21. Trends related to household electricity use in the EFOM baseline.

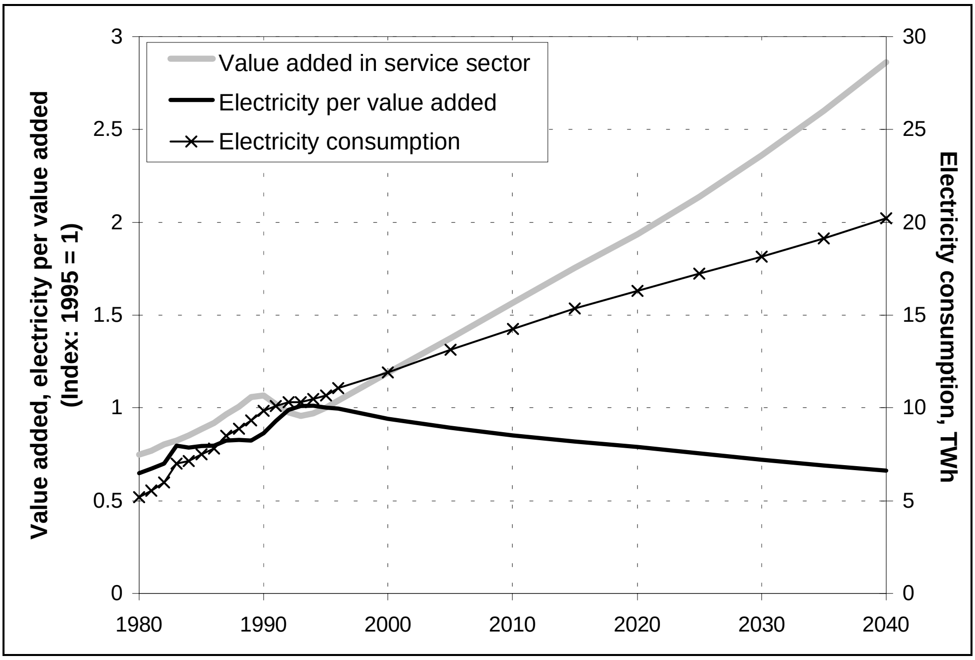

Figure 22. Trends related to service electricity use in the EFOM baseline.

6.2.4 Transport

Between 1960 and 1990 the volume of passenger transportation was continuously and rapidly increasing in Finland. During the recession in the early 1990s the growth ceased, but was revived again during the latter half of the decade. The historical development and future projections used in the present study are shown in Figure 23. Modal splits were discussed previously in Section 5.3.2. The published projections for passenger transport volumes differ considerably from each other. While the estimates of the Finnish National Road Administration (Finnra 1995) and that used in the VTT LIISA model are reasonably similar, the projection of the Ministry of Transports and Communication (MoTC 1998) is much higher, as illustrated in Figure 24.

Extending the projections beyond 2020 is, of course, highly speculative. According to a long-term projection made by the road administration, passenger transport volumes on roads could turn into a decreasing trend after 2025 due to decreasing population. In the present study, however, it has been assumed that

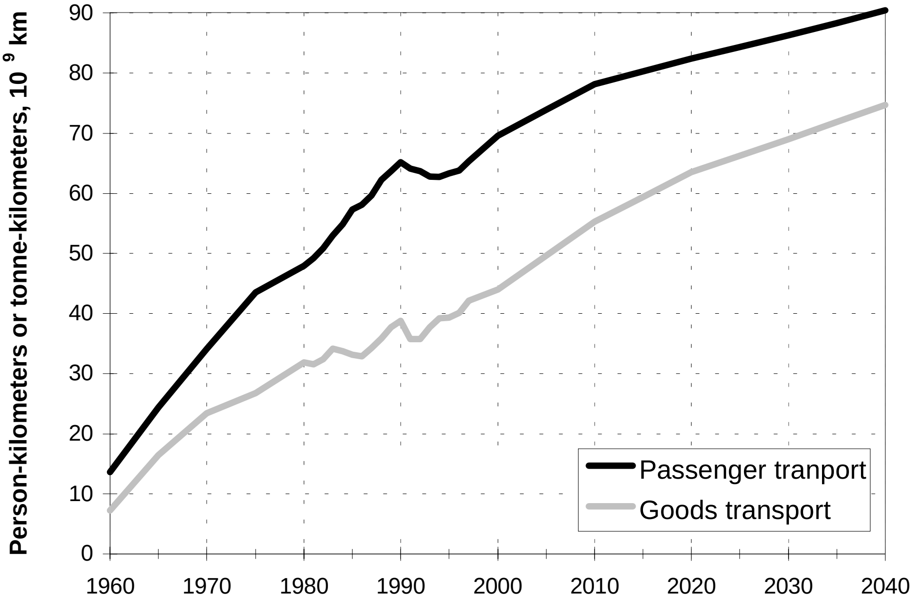

Figure 23. Scenarios for inland passenger and goods transport.

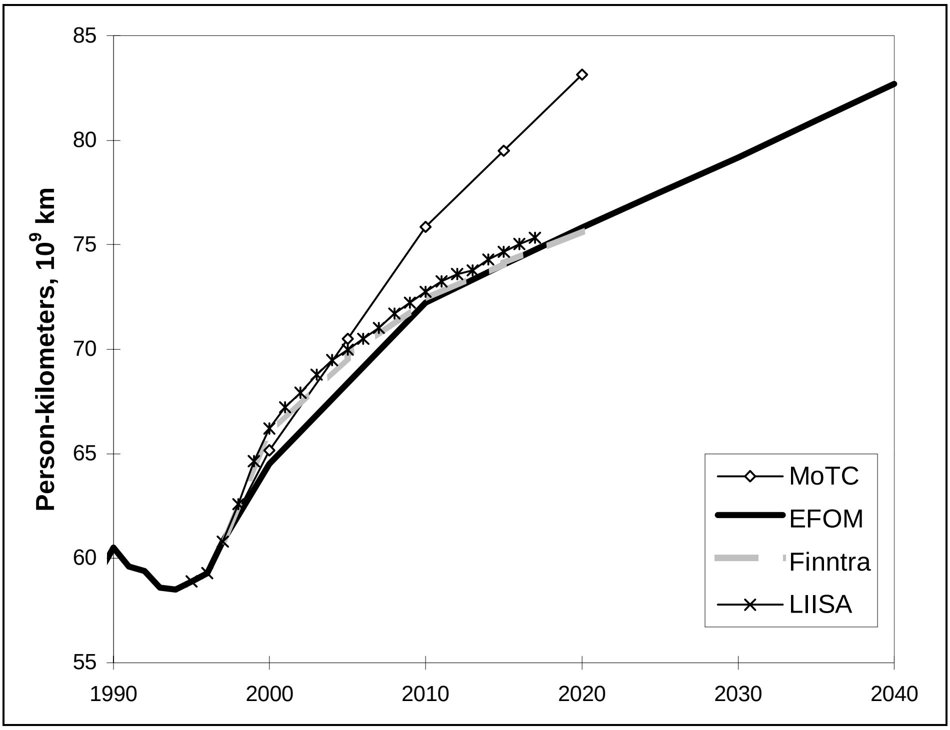

Figure 24. Comparison of projections for passenger transport on roads (Data adapted from MoTC 1998, Mäkelä et al. 1997, Finnra 1995).

the highest projection for 2020 will eventually be reached around 2040. The average annual growth would be decreased to about 0.3% between 2030 and 2040, while during the 1980s the growth was still as high as about 3% per annum.

For goods transport the published projections are much more consistent. Both the ministry and the road administration estimate that the volumes of inland goods transport will increase by about 60% between 1996 and 2020. The EFOM scenario conforms quite well with these estimates. With regard to the considerably high overall growth in transport volumes, the assumptions on the relatively rapid improvements in the fuel economy (see Section 5.3.2) may not be unrealistic, as the turnover rate of the vehicle stock would be high.

6.3 Supply scenarios

6.3.1 Supply of fuels

The utilisation of CO_2 neutral and low-carbon energy sources in the energy system has a very important role in greenhouse gas abatement. In Finland the most significant CO_2 neutral energy sources are nuclear power, hydro power, wood fuels, and pulping liquors. Natural gas is also a reasonable choice, as for instance when it is substituted for coal. The constraints for the above-mentioned energy sources implemented in the model are:

- Nuclear power generation is limited to the level reached after the ongoing capacity extension programmes.
- Slow increase in hydro power generation is allowed during the whole period due to renovations and some small new plants.
- Imports of natural gas without secure reserves are limited to at most 17 or 20 per cent of primary energy consumption excluding electricity imports and transport fuels.
- Potential for additional use of wood fuels (mainly harvesting residues) is proportional to the industrial use of wood.

The imports of natural gas are limited in the scenarios either to a level, which corresponds to the present natural gas pipe capacity, or to a higher level, which would require a new natural gas pipeline. More precisely, these limits are implemented as relative fractions of the total primary energy consumption excluding electricity imports and transport fuels. These latter energy sources are completely imported and thus would in any case increase the dependency on imports in the energy supply. The limits for the maximum level of gas imports without extra reserve storage are chosen to be 17 and 20 per cent. If these limits are exceeded, the model will require additional investments in reserve storage, corresponding to 75% or 25% of the amount in excess in the Gas 17% and Gas 20% cases, respectively. The storage requirement thus makes gas imports larger than the security limit feasible in both cases but much more costly in the Gas 17% case.

In the Finnish energy economy biomass use is exceptionally large in scale compared to most other European countries. In 1990 biomass accounted for 13% of the total primary energy consumption. As regards the production of biomass fuels the wood processing industry plays a major role. Remarkable quantities of wood residues are generated as byproducts of the main processes within the industry. The largest volumes are accumulated in the form of waste pulp liquors containing the non-cellulose parts of wood. Substantial amounts are also generated in the form of bark, sawdust, and various kinds of other waste wood. The use of firewood proper, i.e. wood initially assigned to energy use, accounts for less than 25% of the total biomass fuel consumption. The extent to which further measures are to be taken to promote expanding use of biomass is currently one of the key issues of the energy policy debate in Finland.

The technical potential for increased use of biomass in the future is estimated to be considerable, up to 25% of the total primary energy. The economic potential will, however, depend greatly on the development of the prices of biomass fuels compared to the competing alternatives. In addition to the baseline scenario, also more optimistic assumptions on the development of the costs of biomass fuels and advanced utilisation technologies have been applied in the present study. However, optimistic estimates have been used only for the most important biomass fuel, wood. The assumptions for the prices and supply potential for non-byproduct biomass fuels were already presented in Table 26. Regarding the utilisation technologies, the costs have been, in general, assumed to be 15 per cent higher in the baseline scenario than in the optimistic case.

6.3.2 Energy transformation

In the energy transformation sector a large number of constraints are required for realistic behaviour of the model, and for the purposes of scenario analyses. In the present study, important energy system constraints in the model include:

- Net imports of electricity are at maximum 5 TWh per annum.
- The total potential of wind power increases smoothly to 8.5 TWh/a by 2030. About 50 per cent of this potential consists of off-shore or arctic wind power.
- Mass incineration of MSW is limited to about 20 PJ/a, which corresponds to somewhat more than 50 per cent of annual MSW generation in Finland.

- Utilisation of biogas and RDF are both limited to 5 PJ/a.
- Present emission standards for sulphur and nitrogen oxide emissions are taken into account.

In addition, the prices of different fuels have a considerable impact on the structural development of the energy sector. The fuel prices assumed in the study and the potential of wood fuel supply were presented in Section 5.2.

The new utilisation technologies considered for biomass are integrated gasification combined-cycle (IGCC) and pressurised fluidised bed combustion (PFBC). With these technologies also solid fuels other than wood, such as coal and peat, can be utilised. In the baseline cases for biomass use the capital and fixed costs are 15 per cent higher than in the optimistic cases. Generally, the costs are assumed to decrease by about 10 per cent between 1998 and 2010 (0.9% per annum) in both cases. It has been assumed that these technologies will reach a commercial level around 2010, and thereafter the decrease in costs will cease.

Baseline or optimistic assumptions are applied also to the development of other new energy technologies. Alternative assumptions have been applied to the following technologies: wind power, solar power, solar heat (for water and space heating), fuel cells for power and heat, and electric cars in the transportation sector. The costs of wind power are today relatively well-known, and therefore only the maximum utilisation potential is varied for wind energy. The potential will increase to only 0.8 TWh/a by 2030 in pessimistic cases and to 8.5 TWh/a in optimistic cases. For other new technologies two different cost scenarios have been used in the same way as for IGCC and PFBC described above.

6.4 Scenarios for the greenhouse gas abatement

6.4.1 Emission reduction commitments due to the Kyoto Protocol

The EU commitment in the Kyoto Protocol is to reduce emissions by eight per cent from the 1990 level between 2008 and 2012. In the calculation, an average of the emissions between 2008 and 2012 is used to compensate for annual fluctuations of the emissions, e.g. due to poor precipitation, which decreases hydro-power generation, and possibly increases emissions. The EU has shared the emission reductions between its member states in June 1998. Finland's national commitment is to return the emissions to the 1990 level. In practice, this commitment requires implementation of quite extensive reduction measures, because, for instance, in 1996 the Finnish CO_2 emissions were about 10 per cent higher than in 1990 (Statistics Finland 1998b).

The reduction objective for calculations in this study is fixed according to the Kyoto Protocol, but only the emissions of CO_2, CH_4 and N_2O are included, because the significance of other gases mentioned in the Protocol is so small – less than 1 per cent. In addition, the emissions of these other gases are very poorly known. The objective is calculated by converting all three gases to carbon dioxide equivalents with GWP(100a) factors (see Section 3.3). The calculation of the commitment level has been done basically in accordance with the latest official inventory, which has not been published yet. These methods are used in EFOM as well. However, there are some exceptions to the latest official inventory. All fugitive CO_2 emissions, e.g. from peat production, are excluded in this study. CO_2 emissions due to non-energy use of petroleum products and due to agricultural lime and dolomite use are also excluded. In addition, CH_4 emissions are somewhat smaller in this study, because the assumed fraction of carbon converted to landfill gas is smaller. The calculated reduction commitment, or the 1990 level, for the Finnish greenhouse gas emissions is presented in Table 34.

Consequently, the mean value of the GWP weighted Finnish greenhouse gas emissions between 2008 and 2012 should be at most 67.2 Tg (CO_2 equiv.) in the calculations in this study. This can be described with Equation 7.

Table 34. The amounts of Finnish greenhouse gas emissions considered in the study in 1990.

Gas	Emission (Gg)	GWP(100a) factor	CO_2-equiv. (Tg)
CO_2	55 000	1	55.0
CH_4	313	21	6.6
N_2O	18	310	5.6
Sum			67.2

$$\frac{1}{5}\sum_{i=2008}^{2012} E_{total,i} \leq E_{total,1990} \tag{7}$$

where $E_{total,i}$ is the total greenhouse gas emission in the year i. In scenarios, in which reduction objectives are allocated to CO_2 only, CO_2 emissions are allowed to be on average at most 55 Tg (CO_2) between 2008 and 2012.

In the EFOM model the calculation period (in this case 1995–2040) is divided into sub-periods, at the endpoints of which the variables are calculated. It is assumed that the change in variables is linear between these endpoints. In this case the annual emissions between endpoints can be estimated as linear combinations of the emissions in the endpoint years with the help of equation 8.

$$E_t = E_{t_0} + i \cdot \frac{E_{t_1} - E_{t_0}}{t_1 - t_0} \tag{8}$$

where t_0 and t_1 are endpoints of a sub-period ($t_0<t<t_1$), E_t is the emission in the year t, and $i=1\ldots(t_1-t_0-1)$. Sub-periods around the year 2010 are 2005–2010 and 2010–2020. Therefore the calculations of emissions in 2008 and 2009 are based on the emissions in 2005 and 2010. Correspondingly, the calculation of emissions in 2011 and 2012 are based on the emissions in 2010 and 2020. After these calculation steps the reduction objective can be written as:

$$\frac{1}{5}\left[\frac{6}{10}E_{2005,total} + \frac{41}{10}E_{2010,total} + \frac{3}{10}E_{2020,total}\right] \leq E_{1990,total}\,. \tag{9}$$

The emission reduction commitments will probably tighten in the future. In this study it has been assumed that in 2025 emissions must be five per cent lower and in 2040 ten per cent lower than in 1990. Between these time points the change over time of the emissions must be linear. These reduction objectives are allocated to particular years and no five-year period is used.

6.4.2 The reduction objectives based on the radiative forcing

Emission reduction objectives can be directly allocated to the impact of emissions with help of radiative forcing (see Section 3.2). In this way it is possible to consider optimal timing of the implementation of the emission reduction measures, because the lifetimes of greenhouse gases in the atmosphere are taken into account. An examination is done by reducing the additive radiative forcing in 2040 due to emissions over the whole period. The effect of historical emissions on the radiative forcing in 2040 could be considered too, but in this study it is excluded. The effects of this kind of approach are studied only in the RF2040 scenario in order to keep the total number of cases down to a reasonable level.

Every annual emission during the period contributes to the radiative forcing in 2040. Annual emissions can be calculated with the help of equation 8 and the annual emissions given at the endpoints of sub-periods. As mentioned earlier, the study period is 1995–2040, which has been divided in six sub-periods. The first three are five-year periods and the last three are ten-year periods.

Radiative forcing coefficients, g_i, for annual emissions can be calculated with Equations 3 and 4, and with Tables 10, 11, and 12. The factors are dependent on gas and the timing of emission. In this case the radiative forcing X_t in a forthcoming year t due to annual emissions in a sub-period $t_0 \rightarrow t_1$ can be calculated with factors and equation 10:

$$X_t = \sum_{i=t_0}^{t_1} g_i E_i = g_{t_0} E_{t_0} + g_{t_0+1}\left(E_{t_0} + \frac{E_{t_1} - E_{t_0}}{t_1 - t_0} \right) + g_{t_0+2}\left(E_{t_0} + 2\frac{E_{t_1} - E_{t_0}}{t_1 - t_0} \right) + \ldots + g_{t_1} E_{t_1} \qquad (10)$$

Equation 10 can be converted to:

$$X_t = \left[\sum_{i=t_0}^{t_1-1} g_i \left(1 - \frac{i - t_0}{t_1 - t_0} \right) \right] E_{t_0} + \left[\sum_{i=t_0+1}^{t_1} g_i \left(\frac{i - t_0}{t_1 - t_0} \right) \right] E_{t_1} \qquad (11)$$

From equation 11 the radiative forcing factors for the endpoint years of a sub-period can be calculated. When the radiative forcings in all the sub-periods are added up, it should be checked that the radiative forcings due to endpoint years are not calculated twice. This can be done by starting the summing index i in the first factor of equation 11 from t_0+1 instead of t_0, except in the first sub-period, where the first year of the whole period must be taken into account.

Table 35. The factors for the calculation of the additive radiative forcing in 2040 (mW/m^2/Tg) .

Year	CO_2	CH_4	N_2O
2000	0.004733	0.026112	1.390906
2005	0.006153	0.047066	1.802654
2010	0.009880	0.125544	2.859008
2020	0.012280	0.275882	3.455287
2030	0.019282	0.856432	5.074146
2040	0.010995	0.749686	2.589088
Constant value		0.642274	

In the calculation of the additive radiative forcing in 2040 the emissions between 1990-95 are also taken into consideration. The emissions between 1990–97 are known, and therefore the variables in the calculation are the emissions of CO_2, CH_4 and N_2O in 2000, 2005, 2010, 2020, 2030 and 2040. The calculated factors for the variables and the constant value due to known emissions are presented in Table 35.

It can be seen in Table 35 that the values of the factors increase with time. This is due to the fact that greater part of the emissions, which have occurred at the beginning of the period, have been removed from the atmosphere than the emissions, which have occurred at the end of the period. Exceptions are the factors for 2040, which are clearly smaller that the preceding ones, because they include weighting only from the previous time period (2030–2040), whereas other factors include weighting for both previous and future time periods.

The radiative forcing objective for the year 2040 is calculated by assuming that the emissions are stable at the 1990 level during the whole period. This value cannot be calculated with the factors in Table 35, because the constant value is in accordance with the real emissions, which are not in 1990 level. The calculation can be done with the help of equation 10 and the data in Table 34. The result is 5.082 mW/m^2.

7. Results

7.1 Development of the energy sector

7.1.1 Primary energy consumption

The structure of primary energy consumption in the scenarios is presented in Figure 25. Energy consumption will grow in all scenarios, but much less in the reduction scenarios, due to efficiency improvements in energy conversion and explicit energy conservation measures, which are discussed in Section 7.2. Electricity imports, hydro and nuclear power generation are utilised to the extent allowed. The use of pulping liquors is also the same in all scenarios, as the production scenario for chemical pulps is assumed to be fixed.

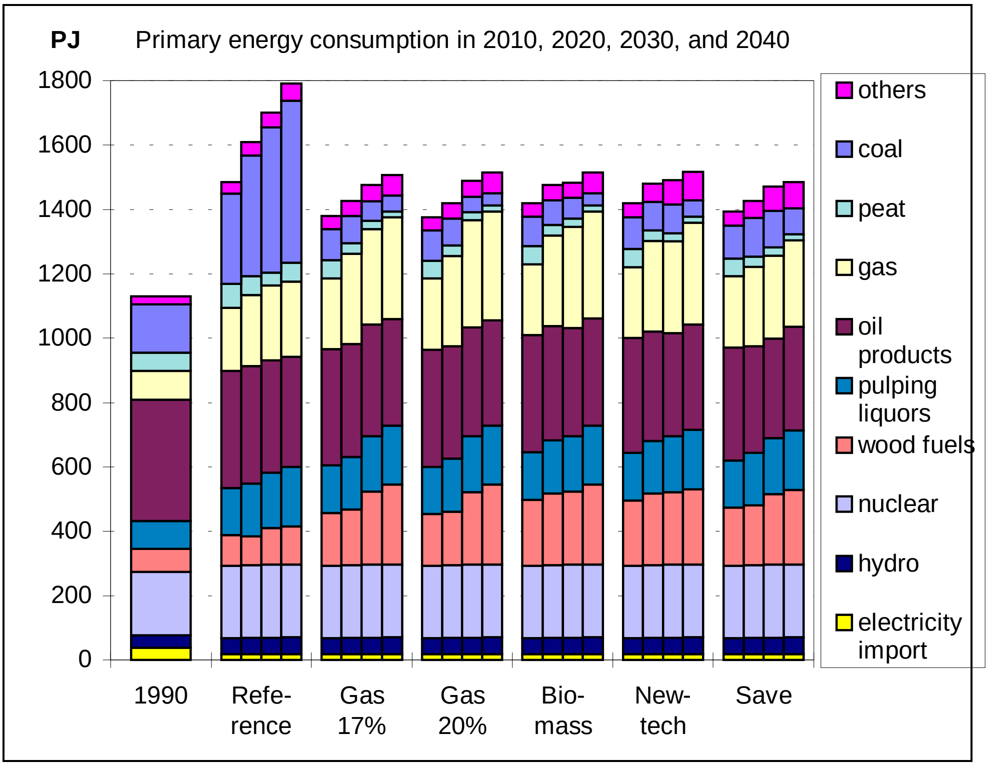

Figure 25. The structure of primary energy consumption in the different scenarios. Adjoining columns are in time order. In the reduction scenarios the emissions of CO_2, CH_4, and N_2O are considered.

The use of oil products decreases slightly due to decreases in direct oil heating of buildings and oil-based district heating. Although the specific fuel consumption decreases in the transport sector, the use of transport fuels would be on quite a stable level due to increases in transportation volumes. The use of coal and peat, which have the highest CO_2 emissions, decreases considerably in the reduction scenarios, as is to be expected.

In all reduction scenarios the use of natural gas is on the same level in 2010 — about 16 per cent of the total primary energy consumption. In the Reference scenario the corresponding share is about 13 per cent during the whole study period. Optimistic assumptions concerning the imports of natural gas do not affect the amount of gas imported until after 2020. In the Gas 20% scenario the use of natural gas increases up to 22.5 per cent of the total primary energy consumption, while in the Gas 17% scenario the percentage is about 2 points lower. Although the optimistic assumptions for natural gas are included in the remaining reduction scenarios, the use of gas will not increase as much as in Gas 20 % scenario. This is due to more optimistic assumptions concerning the cost-efficiency of other available emission reduction options.

The price of biomass already makes a difference in emission reduction in 2010. In the optimistic cases wood fuels (excluding pulping liquors) account for about 14 per cent of primary energy consumption (11 per cent in base cases). In the reference scenario the share is only 6–7 per cent during the whole period. In the latter part of the period the share will increase up to about 15 per cent even in the base cases (with respect to the price of biomass), which implies that both the supply and utilisation potential for wood fuels are quite thoroughly utilised.

Renewable energy sources already today make a very large contribution to the overall energy supply. Nevertheless, the results of the present study indicate that strict commitments to reduce greenhouse gas emissions would significantly enlarge the cost-effective potential for biomass use for energy. This can be seen from Figure 26, which shows the total utilisation of all renewable energy sources taken into account in the study (excluding hydro power). According to published surveys about the supply potential of biomass, the economic potential of wood fuels (excluding pulping liquors) is estimated to be about 160 PJ in 2010 (Helynen & Nousiainen 1996, Alakangas 1997, Asplund 1997). In the

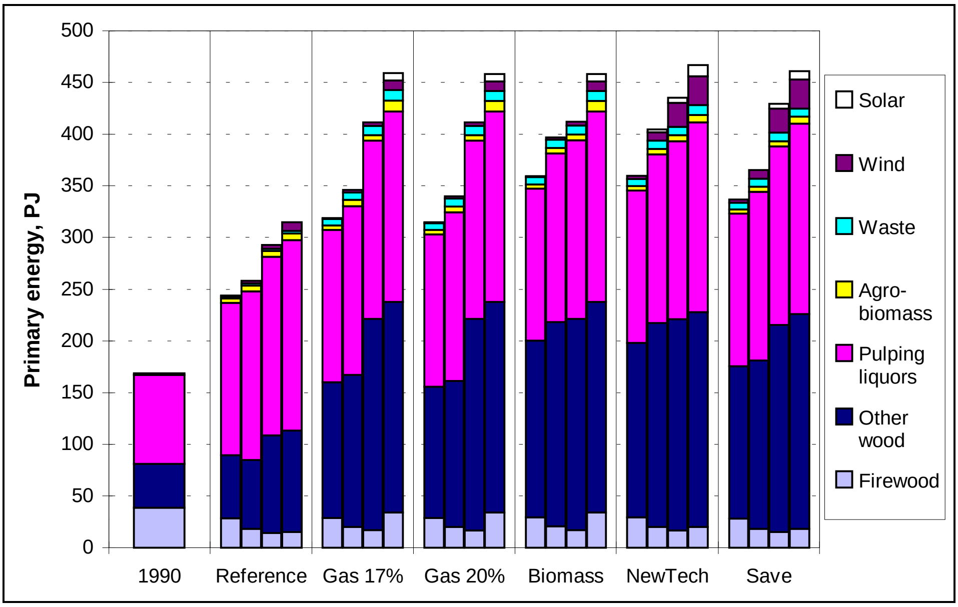

Figure 26. Utilisation of renewable energy sources in 1990 excluding hydro, and corresponding scenario results for 2010, 2020, 2030 and 2040.

scenarios with baseline assumptions for wood fuels, the utilisation of wood for energy would be 155–160 PJ in 2010, i.e. approximately at the estimated level of maximum economic potential.

Notwithstanding, if optimistic assumptions concerning the fuel production costs were to be used, the cost-effective level of utilisation would still be notably higher, about 200 PJ. It should be pointed out that even with the optimistic assumptions, only an amount corresponding to the estimated economic potential has been assumed to be available at a prices below 18 FIM/GJ at CHP or heating plants. Consequently, biomass price levels yet higher than 18 FIM/GJ would become competitive in the reduction cases.

Optimistic assumptions on the price and potential of new technologies affect mostly wind power, when only the structure of energy sources is considered. Wind power generation in 2010 would be at the upper limit defined in the model: 0.9 TWh/a in the optimistic cases and 0.3 TWh/a in the base cases. The difference would grow remarkably after 2010, which can be seen clearly from Figures 26 and 27.

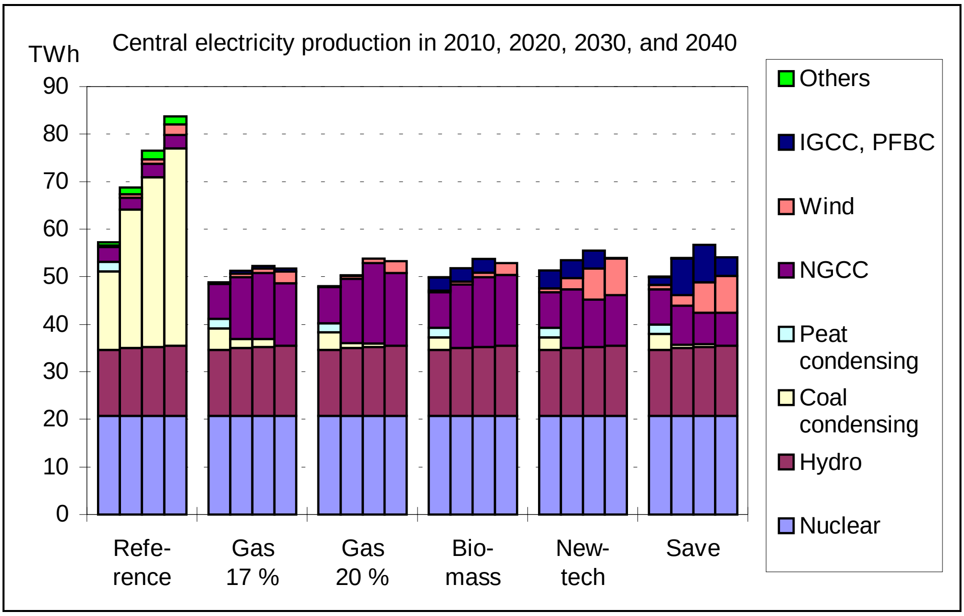

Figure 27. The structural development of central electricity production in the different scenarios. In 1990 the corresponding production was about 35 TWh, and in 1996 about 44 TWh (Statistics Finland 1998b).

7.1.2 Electricity generation

The development of central electricity production is presented in Figure 27. In the Reference scenario the growth in demand is covered with coal-condensing power. In contrast to the Reference scenario, the production volume increases only slightly in the reduction scenarios, and even decreases after 2030. The largest changes in the reduction scenarios are the decrease in coal power and increases in natural gas combined-cycle (NGCC), wind power, and integrated gasification combined-cycle (IGCC). The share of NGCCs is larger in the Gas scenarios, as would be expected. IGCCs would be significant in the last three scenarios, in which the cost assumptions are optimistic. Also wind power production is larger (up to 7.8 TWh/a) in the optimistic cases (Newtech and Save).

The development of industrial electricity production is presented in Figure 28. The production volume is larger in the reduction scenarios, which implies that industry would become more self-sufficient in energy supply. The gasification of peat and wood will increase considerably in all reduction scenarios, but in 2010 their contribution is significant only in the optimistic scenarios (Biomass etc.).

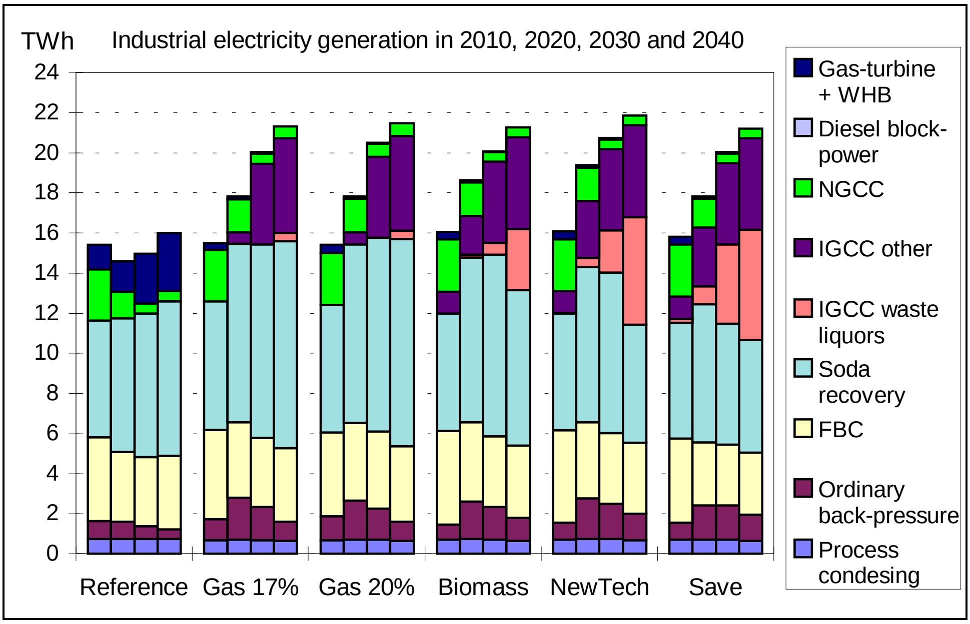

Figure 28. The structural development of industrial electricity production in the different scenarios. In 1990 the corresponding production was about 8 TWh, and in 1996 about 10 TWh (Statistics Finland 1998b).

Also the share of waste liquor based electricity production is larger in the reduction scenarios, which implies that the pulping industries will invest in improved recovery boiler systems with higher power to heat ratios (Komulainen et al. 1994) or waste liquor gasification technologies to increase their self-production of electricity. The relative shares of chemical and mechanical pulping, however, are not allowed to not change in the reduction scenarios. The gasification (IGCC) of waste liquors will replace ordinary recovery boilers significantly in the optimistic scenarios. It is also noteworthy that the position of gas-based combined-cycle technologies would be gradually weakened in the reduction scenarios, while they will be very prominent in the district heat and power sector. The polarisation in the use of biomass and natural gas between the industrial and district heating sectors could be viewed as being somewhat overly pronounced in the results. However, the combined fuel splits are much more balanced.

The combined production of district heat and power would increase in all scenarios, but particularly in the reduction scenarios (Figure 29). The dominating technologies in the reduction cases are NGCC and IGCC (wood, peat, and coal).

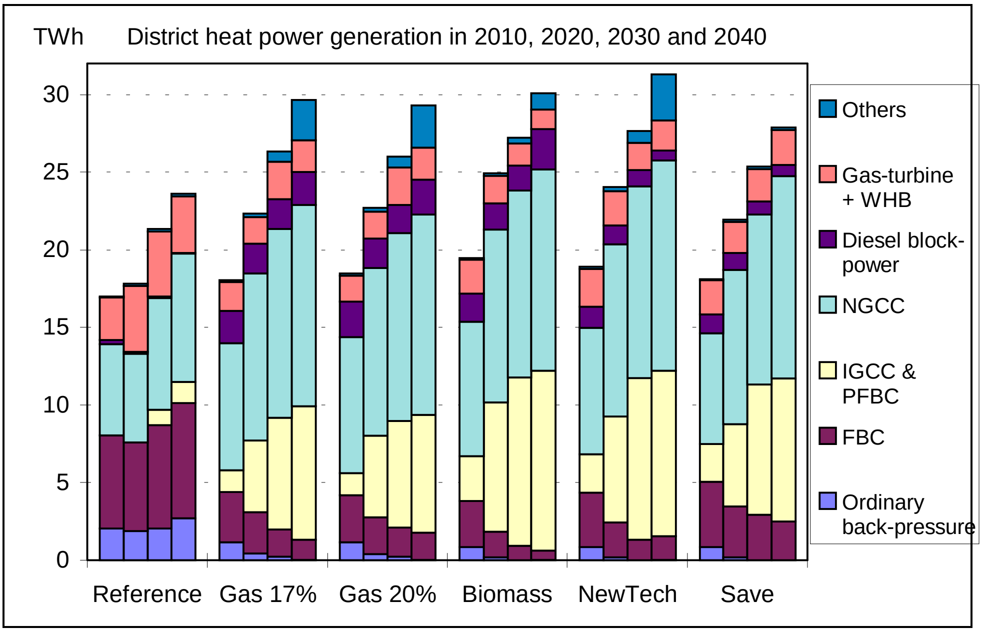

Figure 29. The structural development of district heat power production in the different scenarios. In 1990 the corresponding production was about 8.5 TWh, and in 1996 about 12.5 TWh (Statistics Finland 1998b).

In the scenarios with the least optimistic assumptions decentralised small-scale CHP production based on gas-engines will also have a prominent role. In the more optimistic scenarios larger plant technologies become more favourable and thus diminish some of the decentralised potential. Ordinary (oil or pulverised fuel burners and grate-firing) back-pressure, and fluidised bed combustion, which has high specific N_2O emissions, are utilised much less in the reduction scenarios. The increase in high-efficiency combined heat and power production improves the overall conversion efficiencies of the national energy system.

As discussed earlier, the percentage of CHP is already at present very high in Finland, and most of the larger-size heat loads are extensively being utilised for CHP. Nevertheless, in the situation where strict targets are set for greenhouse gas emissions, considerable additional cost-effective potential for CHP becomes apparent. The share of CHP of the total electricity supply is illustrated in Figure 30.

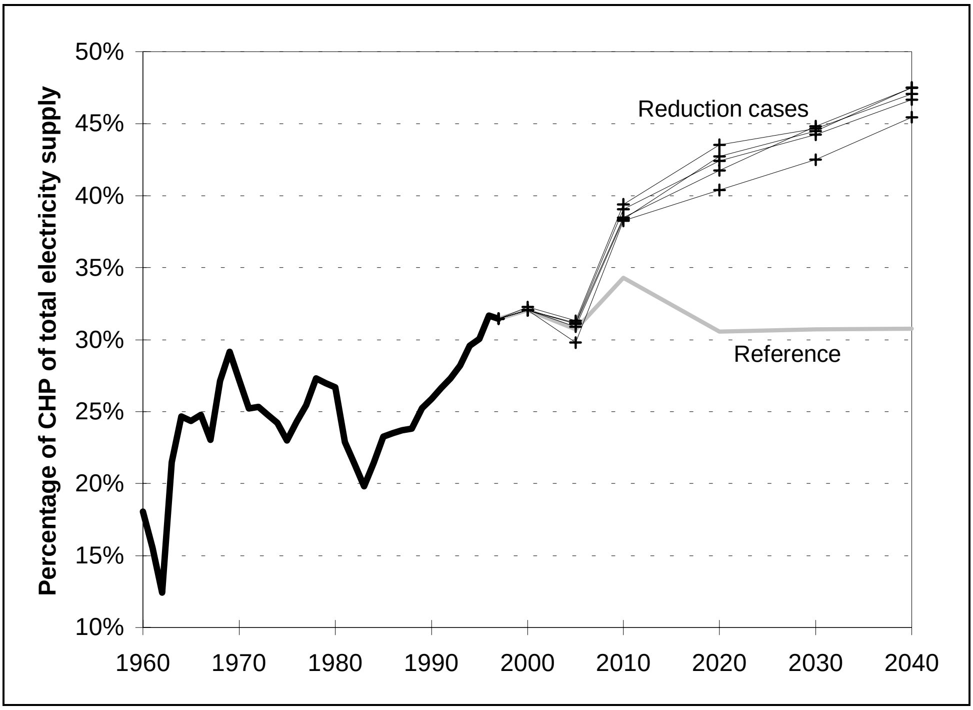

Figure 30. Development of CHP generation in proportion to total electricity supply during 1960–1997 and according to the scenarios.

In the Reference scenario the percentage of CHP would remain approximately at the 1997 level throughout the period studied. The level reached already in Finland thus appears to be nearly optimal, provided that no limits are set for greenhouse gas emissions. In the reduction cases more expensive options to increase CHP generation become cost-effective. The options are largely related to relatively small-scale NGCC or biomass-fuelled plants (small-size FBC as well as IGCC/PFBC, when commercialised). The percentage of CHP would in all reduction cases be increased to 38%–39% in 2010, and to about 45% in 2040.

According to the results, fuel cell CHP technologies would eventually become competitive around 2030, even when using the baseline assumptions for their costs. Shortly after entering the market, in 2040, fuel cells would already gain a significant market share in district CHP generation. The relatively small size-classes projected for commercial fuel cell plants would offer some additional advantage through decentralised generation.

7.2 Developments in the end-use sectors

Electricity use in the consumption sectors is presented in Figure 31. In the Reference scenario the consumption is at a higher level and increases faster than in the reduction scenarios. The decreases in growth are achieved through electricity conservation measures implemented in the reduction scenarios (see Figure 32). In general, increases in total electricity use are largely due to forest industries and other energy-intensive industrial sectors. While in the Reference case the growth in industrial consumption is 63% between 1990 and 2010, in the reduction cases the growth is decreased to 52–57%. Consequently, through the energy conservation measures a saving of 4%–7% in the industrial electricity consumption would be accomplished by the year 2010. In absolute terms the saving would be 3.3 TWh in the Gas 20% case, which happens to be equal to the target suggested for the industrial sector by the Energy Conservation Committee in 1995 (MTI 1995).

Nevertheless, the growth in electricity consumption is significant also in the residential and service sectors. Between 1990 and 2010 household electricity

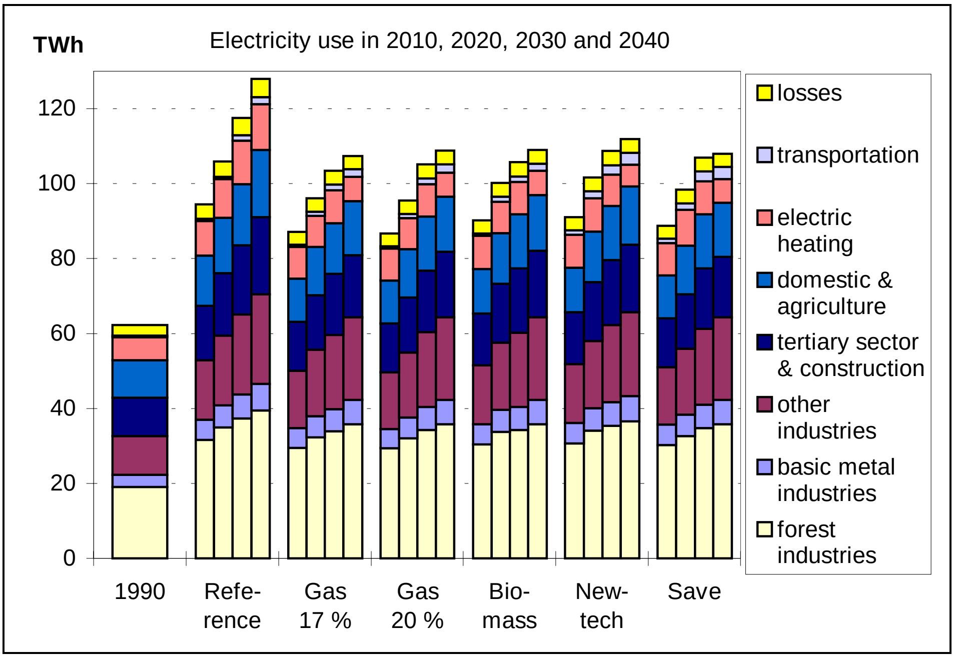

Figure 31. The development of electricity use in the different end-use sectors.

use increases about 49% in the Reference, but the growth is slowed down to 27% due to emission abatement measures. The reduction corresponds to a saving of nearly 15%. In the tertiary sector the baseline growth is 38%, while the growth under the Kyoto Protocol would be only 24%, which is equivalent to energy conservation of 10%.

The extent of energy conservation measures in the different scenarios is presented in Figure 32. Energy conservation would be implemented to the largest extent in the Gas 17% scenario, as the assumptions concerning abatement options are least optimistic. Energy saving decreases when the number of optimistic assumptions increases, except in the Save scenario, where the costs of conservation measures are assumed to be lower. The lower costs can be viewed to represent somewhat smaller requirements for the rates of return by the actual decision-makers.

As described earlier, the volume of residential and service buildings is projected to be increased by about 20% between 1995 and 2010, and by about 50% by 2030. Despite this, for example in the MTI EPO scenarios (MTI 1997a) the total final energy use for heating was assumed to be only a few per cent larger in 2025 than in 1995 (about 215 PJ). The results from the present study are quite similar. The final energy use for heating is shown in Figure 33 for the Gas 20% scenario. According to the results, measures to save up to of 9% of the total

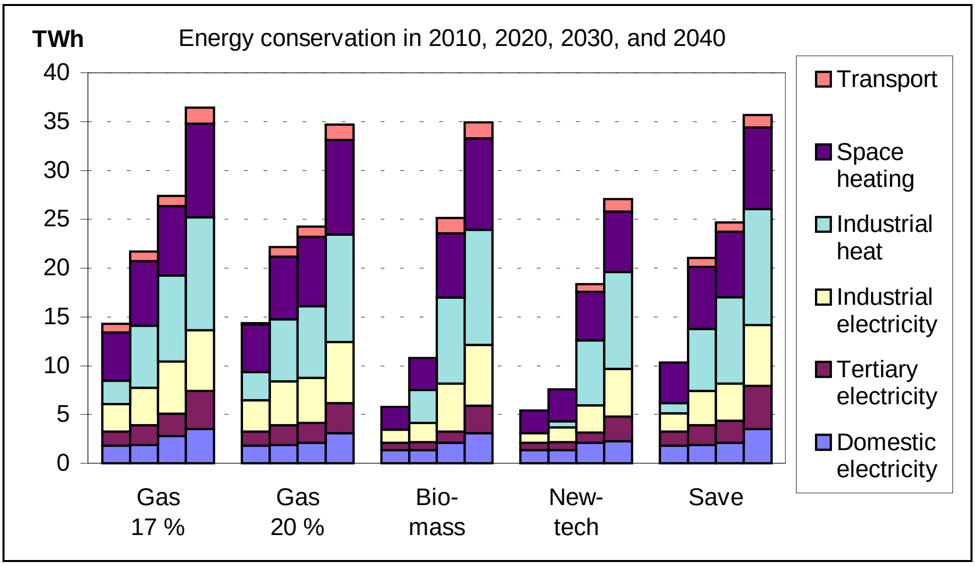

Figure 32. Energy conservation in the different scenarios.

heating energy use would become cost-effective before 2010 due to the emission targets. In reality the implementation would have to be made more gradually. In 2025 the total final energy consumption would be practically at the same level as in 1995.

The use of heat pumps in detached houses would cover in the baseline cases (Gas 17%, Gas 20%, and Biomass), about 3% of the total heat demand in 2010, and 7% in 2040. Under the optimistic assumptions the market share would be only slightly larger, about 8% in 2040. The role of solar heating systems would still remain negligible in 2010 under the baseline assumptions. In 2040, however, they would cover about 11% of all the space heat consumption in single-family houses. In the optimistic cases solar space heating would gain only few additional markets, the share being in 2040 about 12%. Separate solar water-heating systems would not become widely used until around 2040.

The relative growth of electricity use is fastest in the transportation sector, especially in the Newtech and Save scenarios, because in passenger transport electric cars would gain a market share up to 25 per cent of the total transport volumes in 2040. In a similar way electric vans would cover a significant part of the total transport by vans, but as heavier trucks and trains dominate the goods transport, the overall impact of electric vans on the energy consumption and emissions would remain small.

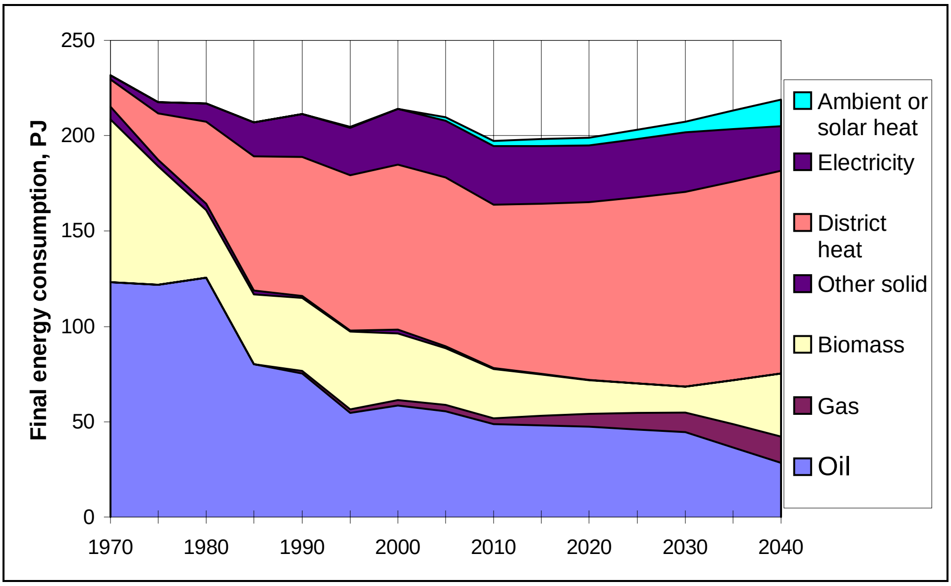

Figure 33. Development of final energy use for heating in the Gas 20% case.

7.3 Development of the greenhouse gas emissions

7.3.1 Emission reduction based on the amounts of gases emitted

Greenhouse-gas emission reductions have been examined with various reduction targets in this study. Targets has been aimed at three GHGs together, at CO_2 emissions only, and at the radiative forcing due to emissions (CO_2, CH_4, and N_2O) between 1990 and 2040. The development of the Finnish greenhouse gas emissions in the reduction cases and in Reference scenario are presented in Figure 34. The emissions in different GHG emission reduction scenarios follow nearly the same path, because the target is the same. Consequently, they are presented as one scenario. The radiative forcing scenario, RF2040, is presented in Figure 34 as well, but the results are discussed in Section 7.3.3.

In the Reference scenario the CO_2 emissions would increase continuously due to growing energy consumption and fossil fuel use. In the GHG and CO_2 reduction cases they would decrease quite rapidly after 2005. One reason for this is that many fossil fuel power plants will reach the end of their economic life after 2005, and therefore it is not economical to start using other energy sources until it is really necessary. Rapid decrease after 2005 implies that total emissions must be reduced below the 1990 level, because the Finnish GHG emissions should be on the 1990 level between 2008 and 2012. In other words, if emissions are above the target level in the beginning of this period, then they must be reduced below the target level in the end of the period.

In the case of “Reduction of all GHGs”, emission reduction measures are allocated in an optimal way to the three different gases with respect to costs. For example, it is not necessary to reduce CO_2 emissions exactly to the 1990 level between 2008 and 2012, because CH_4 and N_2O emissions already decreased after 1990, and because there are some CH_4 and N_2O control options, which are cost-effective compared to the CO_2 reduction measures. Consequently, CH_4 and N_2O emissions would decrease far below the 1990 level in 2010. In the case of “CO_2 reductions only”, carbon dioxide emissions decrease to the 1990 level on average between 2008 and 2012.

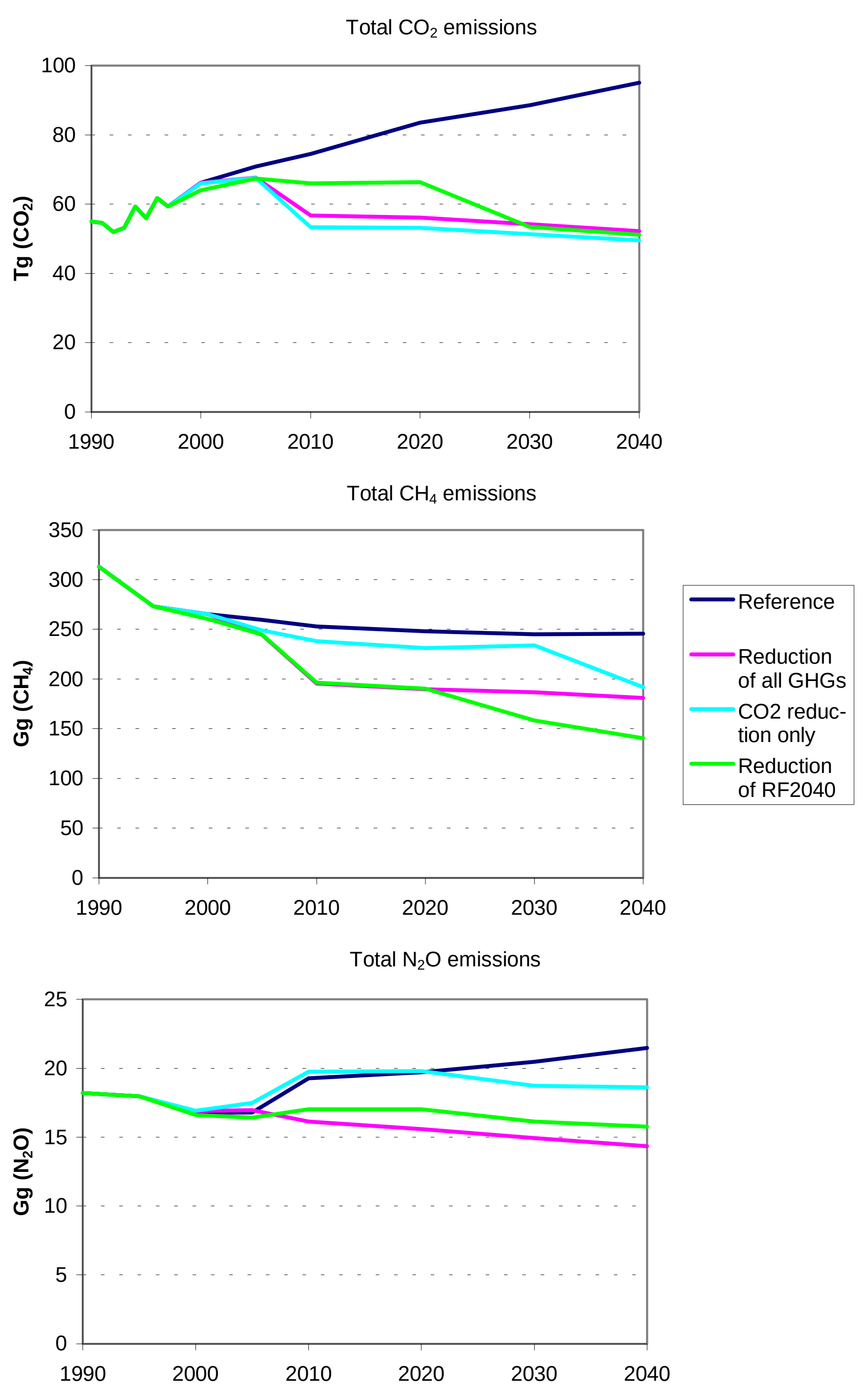

Figure 34. The development of the Finnish greenhouse gas emissions with alternative reduction targets.

Methane emissions are quite stable after 2000 in the Reference scenario. The downward trend in the 1990s is due to decreases in the amounts of cattle and landfill waste. Less waste is put in landfill nowadays than at the beginning of the 1990s due to the waste management policy in Finland. The number of cattle has decreased, because the agricultural subsidy system has changed, and because there was some overproduction in the beginning of 1990s.

In the case of "Reduction of all GHGs" CH_4 emissions still decrease after 2000. This is partly due to utilisation of the combustible content of MSW as energy up to 60 per cent of the potential, which corresponds to 5 PJ in primary energy terms. This measure would also be used in the case of "CO_2 reductions only", because wastes are counted as "CO_2 neutral" fuels. Landfill gas recovery affects mainly methane emissions. Large decreases in emissions are achieved in the case of "Reduction of all GHGs" after 2005 and in the case of "CO_2 reductions only" after 2030, through the introduction of landfill gas recovery. In both cases the recovery rate would increase up to 70 per cent in big landfills after implementation, and in the first case up to 50 per cent in small landfills. The landfill gas recovered would be utilised for energy in larger landfills and burned in a torch in small landfills. Recycling of paper and board remains at its maximum limit even in the Reference scenario, and therefore it would have no effect on CH_4 emissions. Other CH_4 abatement measures in the waste sector (mass incineration; composting and anaerobic treatment of organic waste) have been found to be non-cost-effective, because they remained at their minimum limits in all scenarios, except in RF2040 (see Section 7.3.3).

The CH_4 emissions from the agricultural and energy sectors are quite stable in the Reference scenario and in the reduction cases as well. According to the results, the CH_4 reduction measures studied in agriculture, such as composting and biogasification of manure, are not very cost-effective measures for CH_4 abatement. At the end of the study period bio-gasification of swine manure would be taken into use in the GHG reduction cases; although, this would have only a marginal effect on emissions.

In the Reference scenario the N_2O emissions would increase after 2005 due to increased use of coal and fluidised bed combustion (FBC). Emissions from other sectors would change only slightly during the period. In the case of

"Reduction of all GHGs" the abatement measures in nitric acid production and the replacement of FBC with other techniques (see Figure 29) in district heat power generation would decrease the total N_2O emissions. In the case of "CO_2 reductions only" the emissions follow at first nearly the same path as in the Reference scenario, because CO_2 abatement originates expanding utilisation of biomass in fluidised bed boilers, but later they decrease slightly due to new energy techniques and saving measures.

7.3.2 The development of carbon dioxide emissions by the fuel consumption sector

The large increase of CO_2 emissions in the Reference scenario is due to the fact that coal-condensing power increases in central electricity production. This can be seen with the help of Figure 35 and Figure 27. Emissions from district heat and power would not increase as much. Nevertheless, they would be doubled from the 1990 level by the end of the period. Industrial emissions would increase about 25 per cent during the period. Emissions from transportation, heating and other sectors are quite stable during the whole period.

The CO_2 emissions by sector are also very much the same in the different GHG reduction scenarios, and so they are presented as one scenario. In the reduction case the largest reductions would occur in central electricity production. Coal-condensing power would nearly disappear, and the total production decreases (Figure 27). In the district heat and power sector, emissions would decrease only slightly after 2005, because the volume increases in the reduction cases (Figure 29). In the industrial sector, emissions decrease after 2005 due to large changes in industrial electricity production. Changes, which have an impact on CO_2 emissions, cannot be seen in Figure 28, because it does not show the changes in fuel mix. However, the main reason is that waste wood is substituted for fossil fuels. CO_2 emissions due to direct fuel use in industrial processes would increase in all scenarios, which retards the decrease in total industrial emissions.

7.3.3 Emission reduction based on the radiative forcing

The purpose of the radiative forcing scenario (RF2040) is to study the optimal timing of implementation of emission reduction measures. The radiative forcing

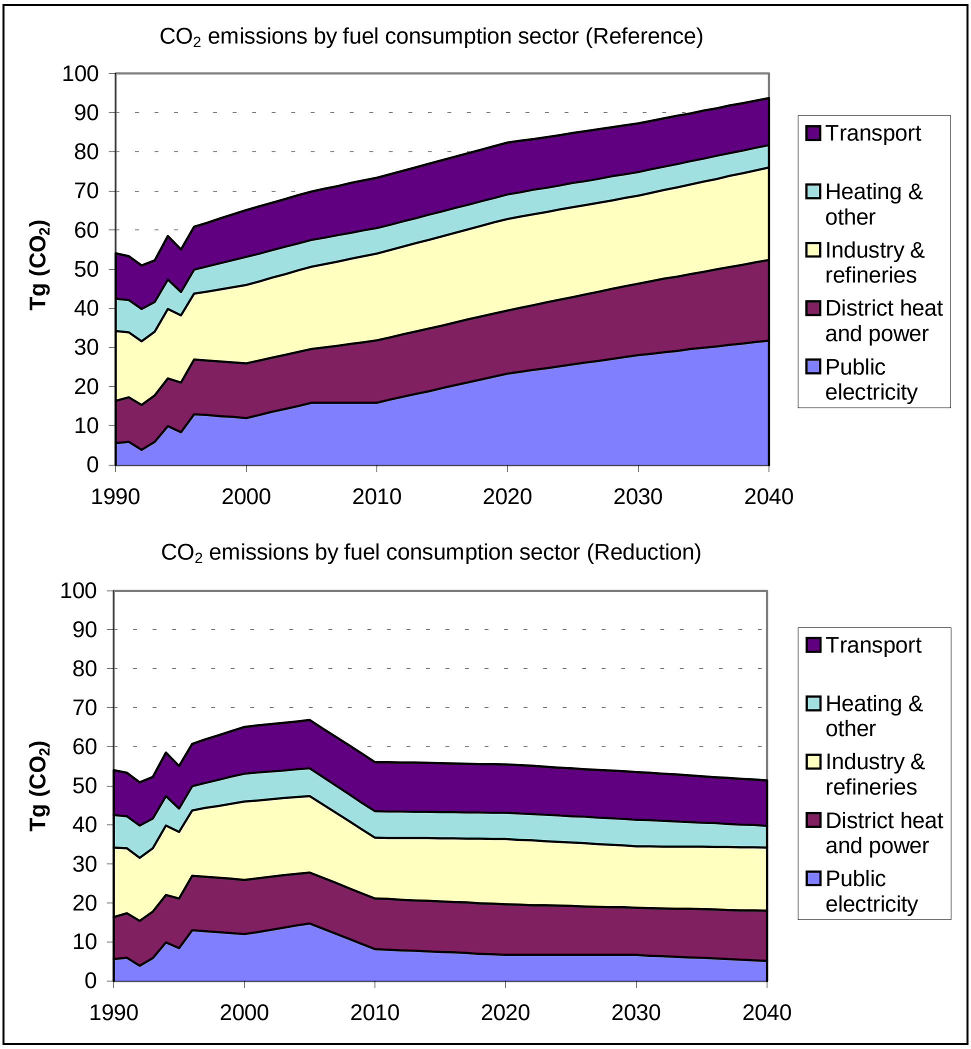

Figure 35. The development of CO_2 emissions by fuel consumption sector in Reference scenario and in the GHG reduction scenarios.

approach is a more scientific and a more complicated way to evaluate emission reduction strategies than the approach which uses emission reduction commitments based on the amounts of direct annual emissions. It takes into account the effects of emissions on the energy balance of the Earth-atmosphere system.

The development of the emissions in the RF2040 scenario is presented in Figure 34. It can be seen that CO_2 emissions are reduced after 2000 in comparison with the Reference scenario. However, the reductions are not so extensive as in the other reduction cases, until the end of the period. Although part of the emitted CO_2 remains in the atmosphere a long time, larger reductions in carbon dioxide emissions are not needed, because it is more cost-effective to invest in the reduction of CH_4 and N_2O emissions.

Especially, it is reasonable to reduce methane emissions in the latter part of the period, because CH_4 has a short lifetime (9–15 years) in the atmosphere, and therefore all methane emitted at the beginning of the period has already been removed from the atmosphere. Methane emissions decrease, even more than in other reduction cases, after 2020 due to the implementation of mass incineration of MSW and organic waste treatment. About 50 per cent of all MSW is incinerated, and over 70 per cent of the remaining amount of organic waste is composted or treated anaerobically. Anaerobic treatment of animal manure would also be implemented after 2020, but the effect on emissions is small.

Landfill gas recovery and the utilisation of waste for energy are on the same level as in the GHG reduction cases. On the other hand, nitrous oxide has a quite long lifetime in the atmosphere, and therefore it is reasonable to reduce N_2O during the whole period. In addition, there are cost-effective N_2O reduction measures comparable with the ones for CO_2, such as the catalytic abatement of N_2O in nitric acid production. The radiative forcing target was given only for one year, which means that the methane emissions are reduced strongly before that year. In long-term target settings perhaps several target-years should be considered.

7.4 Emission reduction costs

7.4.1 Annual reduction costs in the different scenarios

Emission reduction costs are calculated by subtracting the annual costs of the Reference scenario from the corresponding costs of the reduction scenarios. The costs include the total expenditure in the described system that is due to the changes required to reach the target emissions. Indirect costs, e.g. administrative costs, and the costs which may arise due to the changes in the national economy, are not considered in this study.

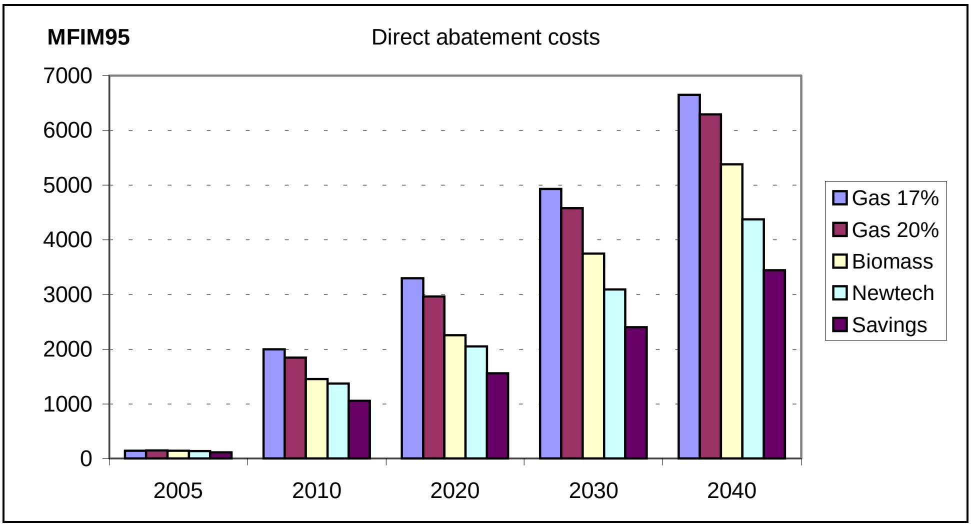

Figure 36. Direct emission reduction costs in the different scenarios.

Abatement costs in the different scenarios are presented in Figure 36. In the commitment period of the Kyoto Protocol the reduction costs are around 2000 MFIM/a in the Gas 20% scenario. In the optimistic scenarios the costs are lower. The costs increase quite rapidly during the subsequent decades due to growing energy consumption and tightening reduction targets. It appears that lower prices of biomass, new biomass utilisation techniques (IGCC, PFBC), and energy conservation measures have the largest impact on the costs, at least in 2010. More optimistic assumptions on the imports of natural gas (Gas 20%) decrease the costs by about 5 per cent. At the end of the period the cost differences between scenarios would be more even, largely because the role of other than biomass-based new technologies would become more prominent.

7.4.2 The abatement cost curve

The abatement cost curve for the Finnish greenhouse gas emissions is presented in Figure 36. The curve has been defined by calculating the reduction costs with a large number of different reduction levels. The point where the costs are zero corresponds to the emissions in the Reference scenario in 2010. However, the costs on this curve are not directly comparable to the 2010 costs in Figure 36, because in the reduction scenarios the total GHG emissions decrease somewhat below the 1990 level in 2010 to achieve the five-year emission reduction commitment. Consequently, the cost which corresponds to zero per cent in

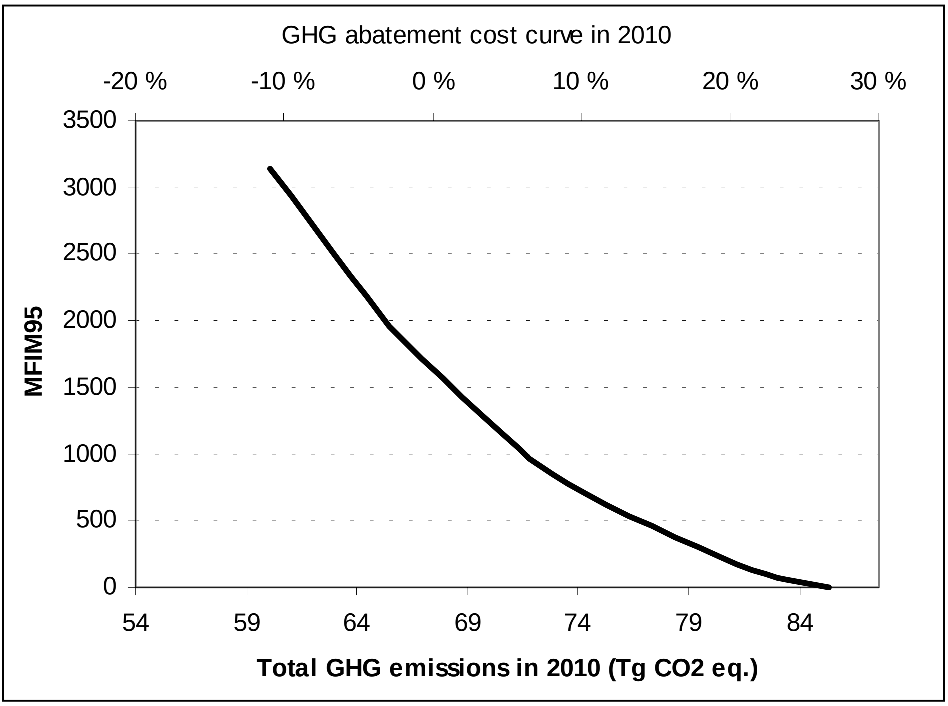

Figure 37. Cost curve for the greenhouse gas abatement in Finland in 2010. The percentage is the change in the amount of emissions compared to the 1990 level (0% = 67.2 Tg). The curve corresponds to the Gas 20% scenario.

Figure 37 is in fact about 200–300 MFIM lower than the reduction cost in the Gas 20% scenario in 2010.

7.4.3 The effect of various reduction targets

In Figure 38 the reduction costs with alternative reduction targets are presented. One can see that if only CO_2 emissions were reduced, the abatement costs would be 20–25 per cent higher than if all three gases were reduced. Marginal costs are about 20 per cent higher as well. This implies that, at least in the case of Finland, the inclusion of CH_4 and N_2O into the Framework Convention on Climate Change brings considerable benefits through more cost-effective emission abatement.

In the RF2040 scenario the abatement costs are much lower than in other cases, except in 2030 and 2040. The reason for this is the development of the emissions (Figure 34). After 2020 CO_2 emissions decrease to the same level as in

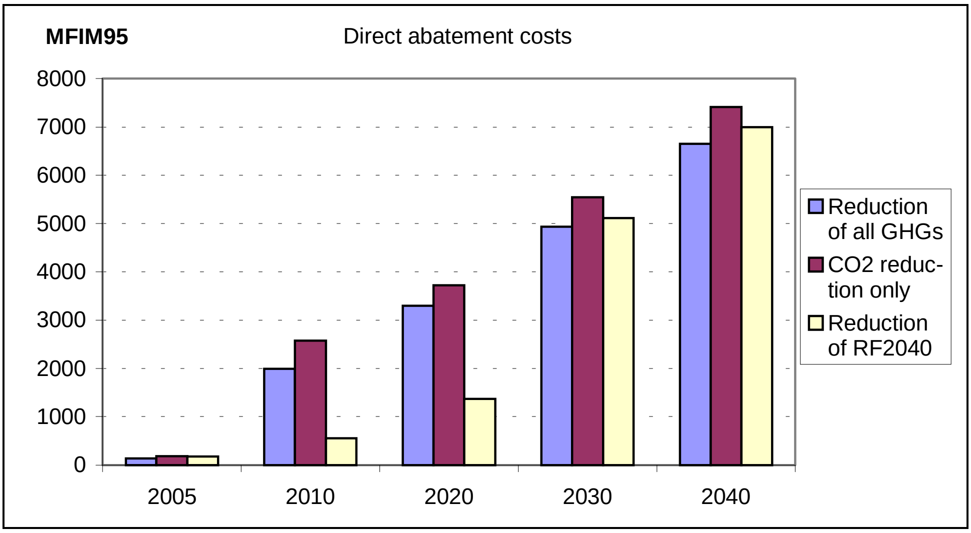

Figure 38. Direct abatement costs with alternative reduction targets in Gas 17% scenario.

other cases, and CH_4 emissions decrease below the level in the case of "Reduction of all GHGs", which increases the total costs to somewhat higher level in 2030 and 2040. However, the abatement costs of the RF2040 scenario are not comparable to the other cases, because the reduction target is not at the same level. The radiative forcing due to the emissions in "Reduction of all GHGs" is about 4 per cent lower than the chosen radiative forcing limit for the RF2040 scenario. In conclusion, emission reduction costs in the RF2040 scenario are lower, because the removal of emissions from the atmosphere is taken into account, and because the reduction target is somewhat "easier".

Marginal costs of emission reduction in the Gas 17% and Gas 20% scenarios with two different reduction targets are presented in Figure 39. Marginal costs are distinctively higher in the case of CO_2 reductions only.

7.5 The nuclear power option

The potential role of nuclear power in emission reduction has been studied with two supplementary scenarios in which nuclear power capacity is allowed to increase. In the Nuclear1 scenario a new unit of the size 1300 MW has been assumed to be operational in 2010. Accordingly, the total nuclear power

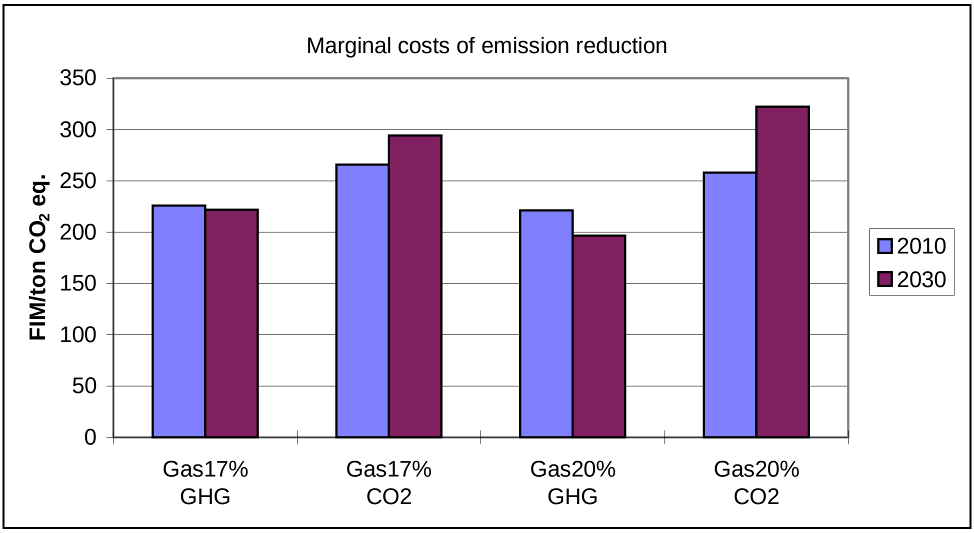

Figure 39. Marginal costs of the greenhouse gas abatement. GHG = abatement of the three greenhouse gases; CO_2 *= abatement of* CO_2 *only.*

generation capacity would then be 3960 MW. In the Nuclear2 scenario the capacity is allowed to grow without constraints to the optimal levels. In other respects these scenarios correspond to the Gas 17% scenario, and they are compared with the same Reference scenario as earlier reduction scenarios.

Primary energy consumption in the nuclear power scenarios is presented in Figure 40. Consumption seems to increase faster than in other scenarios, but a large part of additional growth is illusory due to the computational conversion of nuclear power into primary energy terms. Energy conservation measures are taken in these scenarios as well, but to a lesser extent than in the other reduction scenarios.

If the nuclear power capacity were unlimited, the optimal capacity according to the results would be about 5500 MW in 2010, which implies construction of at least 2 large nuclear power plants. Thereafter the capacity would grow linearly to 9900 MW in 2040.

The contribution of nuclear power generation to total electricity supply in 2010 would be about 33 per cent in the Nuclear1 and about 45 per cent in the Nuclear2 scenario. In 2040 the contribution would be as much as 60 per cent in

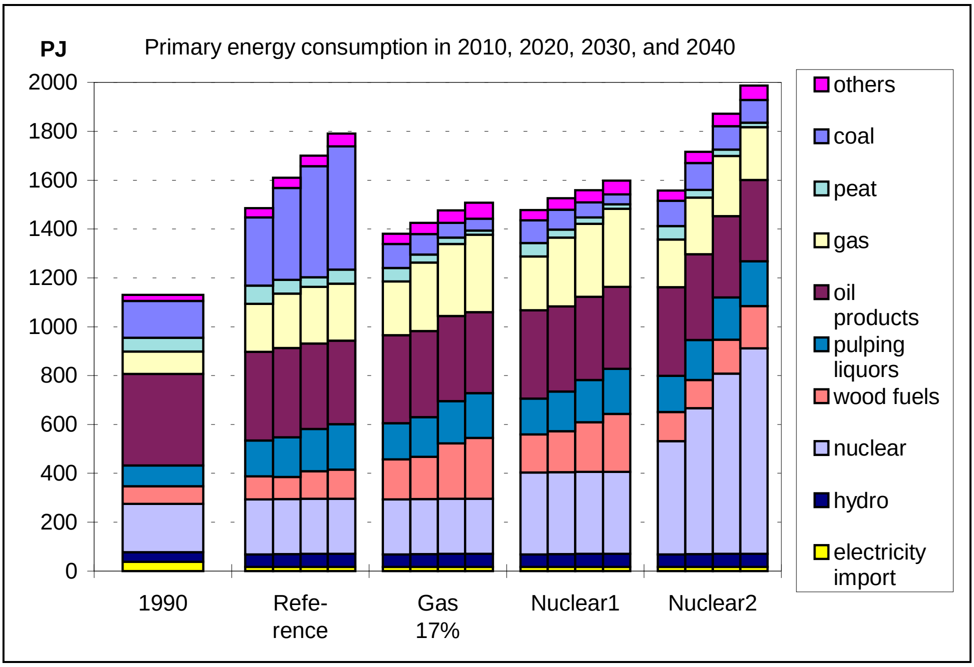

Figure 40. The development of primary energy consumption in the nuclear power scenarios.

the Nuclear2 case. For comparison, in 1997 the contribution was about 27 per cent (Statistics Finland 1998b). The total electricity consumption would be higher in the nuclear power scenarios than in the other reduction scenarios. In the Nuclear1 scenario, industrial and district heat power generation would increase as much as in the Gas 17% scenario, but in the Nuclear2 scenario industrial production would not increase at all after 2005. This implies that the share of purchased electricity would increase quite rapidly. In the forest industry sector this would mean a natural shift towards an increasing share of mechanical pulp production, which, however was not considered in the scenario. Hence, the stabilised self-production of electricity is in this case caused by the weakening competitiveness of industrial CHP in relation to central power production.

In the Nuclear1 scenario the imports of natural gas are the same as in the Gas 17% scenario. Consequently, a single additional nuclear power plant would not eliminate the increase in the use of natural gas, but a larger nuclear power expansion programme would, indeed, have an affect. In the Nuclear2 scenario the level of natural gas imports would be nearly as low as in the Reference scenario.

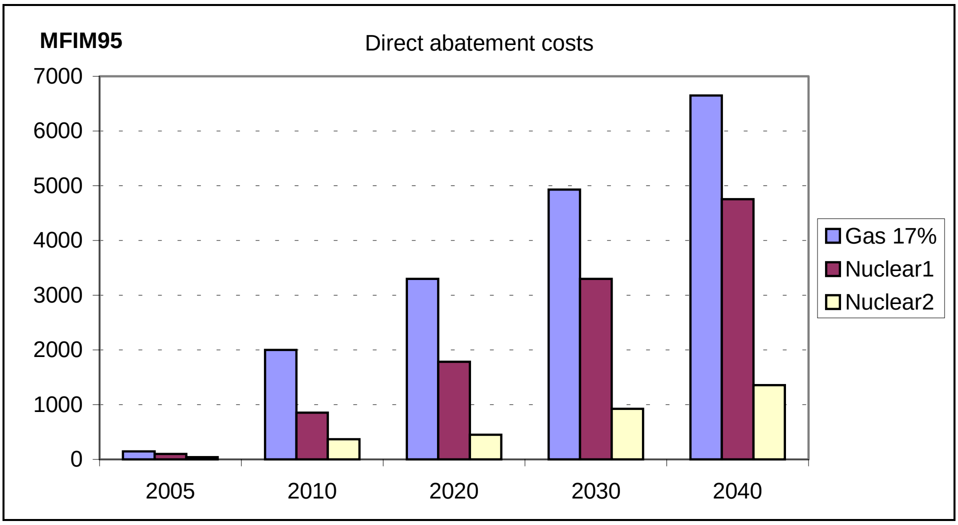

Figure 41. Direct emission reduction costs in the nuclear power scenarios and Gas 17% scenario.

Concerning the use of wood fuels there is a significant difference between the nuclear power scenarios and other scenarios. The total consumption is 5–10 per cent less in the Nuclear1 scenario and 30–40 per cent less in the Nuclear2 scenario.

According to the financial results (Figure 41), one new nuclear power plant (1300 MW) would lower the total emission reduction costs of the Gas 17% scenario by about 1150 MFIM in 2010, and even more in the subsequent years. In the Nuclear 2 scenario the abatement costs would be very small compared to any other reduction scenario.

8. Discussion and conclusions

In Finland carbon dioxide accounted for about 84% of all greenhouse gas emissions in 1995, when counted as carbon dioxide equivalents. Methane emissions were about 7%, and nitrous oxide emissions about 8% of the total greenhouse gas emissions. About 98% of the CO_2 emissions originate from the supply, conversion and end-use of energy, the rest being due to industrial processes.

Official national statistics indicate that energy-related carbon dioxide emissions increased about 10% between 1990 and 1997. The amount of nitrogen oxide emissions, on the other hand, has been quite stable, and methane emissions have decreased as much as 30% due to changes in waste management policies and agriculture. Combining these changes, the estimated total increase in greenhouse gas emissions has been about 4% between 1990 and 1997.

According to the burden-sharing agreement made within the EU, Finland has committed herself to the target of returning the total amount of greenhouse gas emissions to the 1990 levels. Although the target for the EU as a whole is an 8% decrease in emissions, the Finnish target can be assessed as equally or even more demanding than the average for EU countries. Such an assessment can be based on the national characteristics of the Finnish energy economy. Energy-intensive industries have an exceptionally prominent role in the overall energy consumption, while at the same time the supply system is less carbon intensive than the average in EU countries. Large utilisation of CHP has raised the average energy efficiency of electricity generation to a higher level than in any other OECD country relying substantially on combustible fuel-based generation (Lehtilä et al. 1997b). Furthermore, according to international statistics (e.g. IEA 1998), also the utilisation of CO_2 neutral biomass for energy is in Finland more extensive than in any other OECD country.

Projections for the next few decades in Finland expect a relatively rapid economic growth, which is largely based on energy-intensive basic industrial sectors. Taking that the possibilities for efficiency improvements or switching to less carbon-intensive fuels are limited, the growth in the energy-intensive sectors will make it very difficult to avoid increasing the use of fossil fuels and carbon dioxide emissions in Finland.

Nevertheless, many technical options do exist for the control of emissions. Perhaps most obviously, energy use can be reduced by energy conservation measures. Conversion efficiencies can be further improved by utilising the heat-loads suitable for CHP generation as extensively as possible. Continuous efforts have been made to develop improved technologies for the production of biomass fuels, and promising results have already been achieved. Finland could also try to always stand in the front-line when new and advanced energy technologies are brought into commercial use. Furthermore, the structure of manufacturing industries could be directed towards less energy-intensive products. However, in order to have a positive global effect on emissions, such structural changes would have to be driven by changes in consumption patterns.

In waste management CH_4 emissions can be reduced by decreasing the amount of landfill waste and by recovering the methane released from landfills. Integrated ways to decrease both CH_4 and carbon dioxide emissions are the utilisation of waste and landfill gas for energy production, and the recycling of energy-intensive materials as effectively as possible before waste treatment. Emissions from animal manure can be reduced by anaerobic treatment and bio-gasification.

This study has tried to tackle the difficult issue of identifying the most cost-effective technical options to reduce greenhouse gas emissions. Changing the product mix of industries was, however, not considered as an explicit measure. With respect to the Kyoto Protocol, the domestic measures which would enable the fulfilment of the Finnish national emission commitments are of particular interest. According to the results, the technical options that appear to have the most significance include the following:

- Increasing the use forest residues for energy,
- Increasing the use of natural gas and gas-based combined-cycle technologies as long as security of gas supply can be maintained
- Expanding further the utilisation of CHP where possible,
- Intensified efforts to promote energy conservation in all end-use sectors, particularly in household and tertiary electricity use, and space heating,
- Exploiting the possibilities for integrated methane and CO_2 reduction by utilising waste for energy and through the recovery of landfill gas.

The use of wood biomass for energy would increase significantly in all of the emission reduction scenarios by the year 2010. As the costs of wood fuels were in general assumed to be lower for the forest industries due to synergy advantages, the increases were largest in industrial power and heat generation. Using the baseline assumptions for the costs of biomass, the total use of wood biomass excluding pulping liquors was 150–160 PJ in 2010, while the use was about 109 PJ in 1997. The amount corresponds approximately to the total economic potential estimated for 2010 (Alakangas 1997). Using more optimistic assumptions about the costs, the use of wood was increased to about 200 PJ in 2010. In the optimistic case, however, a rapid commercialisation of IGCC technologies for biomass was also assumed.

The use of natural gas was in all reduction scenarios increased to the maximum allowed in 2010, 6.1 billion m^3, or 220 PJ. As the use in 1997 was 120 PJ, the increase in the use of gas would be as high as 83% in only 13 years' time. Such a rapid increase could only be based on new separate power generation plants using natural gas. In the Energy Policy scenario published by the Ministry of trade and industry, the maximum use in 2010 was assumed to be yet slightly larger, 6.5 billion m^3 (MTI 1997a). In reality the potential for increased use of gas will largely depend on investments in new pipelines connecting the Finnish grid with the European gas networks, as well as on further extensions of the domestic gas network. Rather swift investment decisions would be needed in order to have sufficient time for investments in new gas-fired power and CHP plants.

In 1997 about 77% of the district heat production was already based on combined heat and power generation. Within industrial heat production the percentage of CHP is approximately at the same level. Therefore, the potential for increased power generation in CHP plants appears to be limited. However, the results of the present study indicate that under tight emission reduction targets considerable additional potential would become cost-effective both in the district heating sector and in industrial heat production. In the district heating sector the most favourable technical options appear to be the natural gas combined-cycle in larger communities in southern Finland, and biomass-based CHP in areas with no access to the gas network. In the case of smaller heat loads the competitiveness of gas diesel combined-cycle and gas turbines with waste heat boilers is also improved.

Within the industrial sector the potential for CHP is increased by about 25% between 1995 and 2010 merely through increases in the demand for process heat. The most significant technical options that appear to become cost-effective by 2010 include the expanding use of biomass in FBC-based CHP plants, and improved recovery boiler systems with higher power to steam ratios.

In addition, an accelerated wind power programme could also be considered to be among cost-effective measures for emission abatement already by 2010. An annual production level of about 1 TWh could at best be reached by that time, which would represent a relatively small but yet notable CO_2-free contribution to the overall power supply.

Large uncertainties are related to the assessment of cost-effective potential for energy conservation. Many studies have indicated that there exists considerable energy-saving potential with negative net costs. In the present study, however, such potential was assumed to be unrealisable in practice. Furthermore, an attempt was made to use relatively conservative baseline estimates for the costs of the conservation measures.

According to the baseline results, energy conservation will be among the key measures for achieving the emission targets in Finland. In industrial electricity use the extent of the measures would conform well to the targets set by the Energy Conservation Committee in 1995, but would be smaller in the use of heat. In the residential and tertiary sectors the measures would add up to 9% of heating energy, 15% of household electricity, and 10% of tertiary electricity. Despite the saving in household electricity use, the consumption would still be 27% larger than in 1990. According to a thorough sociological energy study made in 1996, the consumption could, in theory, be decreased by as much as 25% from the 1990 level by the year 2015 through efficiency improvements (Nurmela 1996).

As to the transport sector, several studies indicate that according to the prevailing trends the total fuel consumption of cars will begin to decrease in Finland around 2005 despite the growth of transport volumes (e.g. Korpela & Kalenoja 1997). In line with these projections, large autonomous improvements in the fuel economy of cars were assumed in all scenarios, and little room was left for explicit conservation measures. In practice, policy measures would probably be needed in order to ensure a sufficiently high turnover rate of the vehicle stock. Such measures could include tax shifts from car taxes to taxes on fuel or use of car.

In the waste management sector the most cost-efficient CH_4 reduction measures found in this study were the utilisation of the burnable fraction of municipal solid waste ("energy waste") and landfill gas recovery. These measures are CO_2 reduction measures as well, because they are counted as CO_2 neutral fuels. In large landfills all of the recovered gas would be converted to electricity and/or heat with gas engines and heating boilers. The recovery would be reasonable in small landfills as well, although the recovered gas would not be utilised. The utilisation rate of energy waste is still quite low in Finland, but it will probably increase in near future due to ongoing pilot-projects.

The recovery rate of paper and board would increase in every scenario mainly due to the assumed changes in the raw material mix in paper manufacturing (Figure 12). As the recovery rate is already at a high level in Finland, the effect on CH_4 emissions is, however, quite small. With the rather uncertain cost estimates used, composting and anaerobic treatment of organic municipal waste was less cost-efficient than the other options considered for CH_4 emission reduction. On the other hand, the utilisation of organic waste has other environmental benefits, and, in particular, composting is becoming more common in Finland. Mass incineration of MSW would double from the present level by 2010, but the volume would still be small, about 3.5 per cent of MSW.

In agriculture the CH_4 emission reduction measures were included for only a small part of the emission sources. The CH_4 emissions from the most significant agricultural source, enteric fermentation of animals, could be reduced e.g. by improving the feed, but no data for such measures were available. The composting and anaerobic treatment of animal manure have proved to be quite expensive as CH_4 reduction measures. Nevertheless, the latter would be brought into use after 2030 in the reduction scenarios.

The catalytic abatement of N_2O emissions from nitric acid production was found to be a cost-effective measure, although the upper limit of the unit costs given in the literature (Oonk 1998) was selected. Unfortunately, there are no commercial-scale experiences of this measure, and therefore it might be too optimistic to assume that the N_2O emissions from nitric acid production could be reduced in the commitment period of the Kyoto Protocol. If this measure were excluded from this study, the emission reduction costs would be about 120 MFIM higher in 2010. According to the results, another longer-term measure to reduce N_2O emissions would be the replacement of fluidised bed combustion with other technologies (mainly IGCC) in combined heat and power generation.

The direct annual costs for the technical emission reduction measures were calculated to be around 2000 MFIM in 2008–2012, when baseline projections were used for all scenario assumptions. Using the most optimistic assumptions, the annual costs were lowered to about 1100 MFIM. If CO_2 emissions alone were reduced to the 1990 level, the abatement costs would be 20–25 per cent higher than if the combined emissions of CO_2, CH_4 and N_2O were reduced. Consequently, the integrated abatement of all three gases opens up substantial cost-efficiency gains in Finland.

The marginal costs in 2010 were calculated to be about 230 FIM or 38 ECU per tonne CO_2 equivalent removed, when the most optimistic cases are excluded from consideration. The abatement cost curve derived from the analysis could be used in further analyses concerning emissions trading. To the extent the marginal costs in Finland will, on the average, be higher than in other countries among the parties to the Kyoto Protocol, emission trading between Finland and other countries should be included in the emission abatement measures to be implemented. The marginal costs also correspond to the level of carbon tax that ideally would lead to the implementation of the emission reduction measures required.

The calculation model used in the study does not take into account possible changes in economic activity due to changes in energy prices. To the extent such changes will take place as a result of declines in the relative competitiveness of Finnish industries, indirect costs in the form of GDP losses are involved. Furthermore, in practice the costs of the measures of an extensive emission reduction programme are not evenly dispersed in the economy, and therefore policy measures that would lead to the use of most cost-effective technical options may be difficult to implement. Consequently, substantial implementation costs could be also involved.

Allowing for one additional nuclear power plant to be commissioned around 2010 would have a significant impact on the costs. Looking at the direct costs alone, the total annual costs would be about 1150 MFIM lower than in the corresponding case with no additional nuclear power. Taking into account also all the indirect cost-effects would probably widen the cost-difference further.

Looking into a longer term than just to the first commitment period around 2010, many new energy technologies can be expected to be commercialised. A number of technologies that can be assessed to have some potential importance in Finland during the four next decades were included in the study. According to the results, technologies that are likely to have a considerable role at least in the longer term include wind power, IGCC technologies, heat pumps, solar heating, electric cars, and even fuel cells for CHP production. Nevertheless, the results show that the emission reduction costs increase quite rapidly over the period studied. This is due to the projected energy consumption, which is constantly growing, although the emission reduction targets are at the same time tightening. Consequently, emission reductions will be much more costly in the time beyond the first commitment period around 2010. In reality, energy-intensive industries will probably have to adapt in one way or another to the changes needed for achieving the emission commitments. In the worst case this could involve large structural changes and welfare losses in the national economy.

In one of the scenarios studied, a limit was set to the additive forcing due to Finnish greenhouse gas emissions between 1990 and 2040, which was calculated by assuming that the emissions would be at the 1990 level during the whole period (about 5 mW/m^2, see Chapter 3 and Section 6.4). In comparison with the historical development of the radiative forcing, this value is very large, because nowadays the total radiative forcing due to all historical Finnish GHG emissions is about 3.9 mW/m^2 (see Figure 6). These values cannot be added directly, because a large part of the greenhouse gases emitted before 1990 are removed from the atmosphere before 2040. However, the total radiative forcing in 2040 was almost 7 mW/m^2 in the reduction scenario while it was as high as 8.7 mW/m^2 in the Reference scenario. In conclusion, the radiative forcing due to Finnish GHG emissions would increase considerably in every scenario. In order to stabilise the radiative forcing to the present level, much larger emission reductions would be needed.

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Appendix A: CH_4 and N_2O emission factors

Methane and nitrous oxide emission factors for energy sector have been determined with help of the ILMARI model (Statistics Finland 1997) and CORINAIR inventory guidebook (McInnes 1996). The classification of combustion processes is somewhat more simplified in the EFOM model than in the ILMARI model, and therefore the initial emission factors had to be aggregated. This has been done by calculating weighted mean values with the amounts of fuel utilised in alternative boiler types.

The emission factors were needed for combustion processes in central electricity production, industrial energy production, district heat and power production, transportation, residential sector, and commercial sector. The used factors are presented in Tables A-1 – A-8.

Table A-1. Emission factors for central electricity production.

Production category	Fuel	CH_4 (t/TJ)	N_2O (t/TJ)
Coal condensing power, PF, new	Coal	0.0040	0.0020
Coal condensing power, PF, old	Coal	0.0040	0.0029
Oil condensing power	Heavy and Light Fuel Oil	0.0080	0.0020
Gas condensing power	Natural gas	0.0030	0.0010
Peat condensing power	Peat	0.0020	0.0020
NGCC	Natural gas, Light Fuel Oil	0.0030	0.0010
PFBC	Coal	0.0040	0.0300
IGCC	Coal	0.0040	0.0020
Diesel block power	Heavy Fuel Oil, Natural Gas	0.0020	0.0310
Gas turbine power	Natural gas	0.0030	0.0010
Gas turbine power	Light Fuel Oil	0.0080	0.0010
Gas engine	Biogas	0.0020	0.0310

Abbreviations in Table A-1: PF = pulverised firing, NGCC = Natural Gas Combined-Cycle, PFBC = Pressurised Fluideised Bed Combustion, IGCC = Integrated Gasification Combined-Cycle.

Table A-2. Emission factors for industrial energy production.

Production category/ **Combustion technique**	**Fuel**	**CH_4 (t/TJ)**	**N_2O (t/TJ)**
Process condensing power/**All**	Peat	0.0020	0.0020
	Waste wood	0.0500	0.0020
	Coal	0.0040	0.0020
	Heavy Fuel Oil, Light Fuel Oil	0.0080	0.0020
	Natural gas	0.0030	0.0010
	Other gases	0.0030	0.0010
Back pressure power			
PF	Coal, Peat	0.0035	0.0031
PF	Oil, gases	0.0039	0.0014
CFBC	Coal, Peat, Wood	0.0224	0.0390
BFBC	Coal, Peat, Wood	0.0213	0.0270
Grate		0.0213	0.0027
Soda recovery boiler	Black liquor	0.0010	0.0014
Diesel+WHB	Heavy fuel oil, natural gas	0.0020	0.0310
GT+WHB	POK	0.0080	0.0010
GT+WHB	Gases	0.0030	0.0010
NGCC	Natural gas	0.0030	0.0010
IGCC	Peat, Wood	0.0040	0.0020
IGCC	Waste liquor	0.0040	0.0020
Steam boiler			
Grate/Burner		0.0187	0.0039
Steam boiler, FBC		0.0058	0.0300

New abbreviations in Table A-2 mean: CFBC = Circulating Fluidised Bed Combustion, BFBC = Bubbling Fluidised Bed Combustion, GT = Gas Turbine, WHB = Waste Heat Boiler.

Table A-3. Emission factors for district heat and power production.

***Production category/* Combustion technique**	**Fuel**	**CH_4 (t/TJ)**	**N_2O (t/TJ)**
CHP power plant			
PF, big	Coal	0.0040	0.0020
PF, small	Coal	0.0040	0.0020
All	Heavy Fuel Oil	0.0080	0.0020
All	Natural Gas	0.0030	0.0010
CFBC	Coal, Peat, Wood	0.0111	0.0300
BFBC	Coal, Peat, Wood, REF	0.0145	0.0300
PF, big	Peat	0.0020	0.0020
PF or Grate, small	Peat, Wood	0.0050	0.0300
All	MSW	0.0119	0.0300
GT+WHB	Light Fuel Oil	0.0080	0.0010
GT+WHB	Natural Gas	0.0030	0.0010
NGCC	Natural Gas	0.0030	0.0010
Diesel+WHB	Light Fuel Oil, Natural gas	0.0020	0.0310
Gas engine	Biogas	0.0020	0.0310
PFBC	Coal, Peat	0.0040	0.0300
IGCC	Coal, Peat Wood	0.0040	0.0020
District heat boiler			
FBC	Coal, Peat Wood	0.0099	0.0370
FBC	Coal, Natural gas	0.0033	0.0013
Others	Heavy Fuel Oil, Peat, Wood	0.0138	0.0038
Others	Heavy and Light Fuel Oil, Gases	0.0371	0.0017

New abbreviations in Table A-3 are: REF = Recycled fuel, MSW = Municipal Solid Waste.

Table A-4. Emission factors for transportation (McInnes 1996).

Application/ Vehicle	**Fuel**	**CH_4 (t/TJ)**	**N_2O (t/TJ)**
Passenger transport			
Passenger car	Gasoline	0.0200	0.0010
Passenger car, CAT	Gasoline	0.0300	0.0020
Passenger Car, CAT+	Gasoline	0.0070	0.0180
Passenger Car	LPG	0.0200	0.0000
Passenger Car	Methanol	0.2880	0.0000
Passenger Car	Diesel	0.0020	0.0040
Bus	Diesel	0.0060	0.0030
Ship	Heavy and light fuel oil	0.0020	0.0310
Train	Light fuel oil	0.0020	0.0310
Aeroplane	Kerosene	0.0880	0.0320
Freight transport			
Ship	Heavy and light fuel oil	0.0020	0.0310
Van	Gasoline	0.0200	0.0010
Van	Diesel	0.0060	0.0030
Truck	Diesel	0.0060	0.0030
Train	Light fuel oil	0.0020	0.0310

New abbreviations in Table A-4: CAT = Oxidation catalyst, CAT+ = Three-way catalyst, LPG = Liquefied Petroleum Gas.

Table A-5. Emission factors for single family houses.

Application	**Fuel**	**CH_4 (t/TJ)**	**N_2O (t/TJ)**
Heating	Natural gas	0.0030	0.0010
	LPG	0.0030	0.0010
	Light Fuel Oil	0.0100	0.0020
	Coal	0.0080	0.0030
	Coke	0.0080	0.0030
	Firewood	0.3000	0.0020
	Peat	0.0500	0.0020
	Straw	0.3000	0.0020
Stove	Light Fuel Oil	0.0100	0.0020
	Firewood	0.3000	0.0020
Boiler	Natural gas	0.0050	0.0020
	LPG	0.0080	0.0020

Table A-6. Emission factors for multi-family houses.

Application	**Fuel**	**CH_4 (t/TJ)**	**N_2O (t/TJ)**
Heating	Natural gas	0.0030	0.0010
	Light Fuel Oil	0.0080	0.0020
	Heavy Fuel Oil	0.0080	0.0020
	Coal	0.0080	0.0030
	Coke	0.0080	0.0030
	Firewood	0.0500	0.0020
	Peat	0.0050	0.0020
Stove	Light Fuel Oil	0.0100	0.0020
	Firewood	0.3000	0.0020
Boiler	Natural gas	0.0050	0.0020
	LPG	0.0080	0.0020

Table A-7. *Emission factors for commercial buildings.*

Application	**Fuel**	**CH_4 (t/TJ)**	**N_2O (t/TJ)**
Heating	Natural gas	0.0030	0.0010
	LPG	0.0030	0.0010
	Light fuel oil	0.0080	0.0020
	Heavy fuel oil	0.0080	0.0020
	Coal	0.0080	0.0030
	Coke	0.0080	0.0030
	Firewood	0.0500	0.0020
	Peat	0.0050	0.0020
Stove	Light fuel oil	0.0100	0.0020
	Firewood	0.3000	0.0020
Boiler	Natural gas	0.0050	0.0020
	LPG	0.0080	0.0020

Table A-8. *Emission factors for agriculture, cooking and machines.*

Application	**Fuel**	**CH_4 (t/TJ)**	**N_2O (t/TJ)**
Agriculture, heating	Heavy fuel oil	0.0080	0.0020
	POK	0.0080	0.0020
	Natural gas	0.0030	0.0010
	Firewood	0.3000	0.0020
	Straw	0.3000	0.0020
Cooking	LPG	0.0050	0.0020
	Natural gas	0.0080	0.0020
Machines	Light fuel oil	0.0020	0.0330

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Appendix B: Scenarios for manufacturing

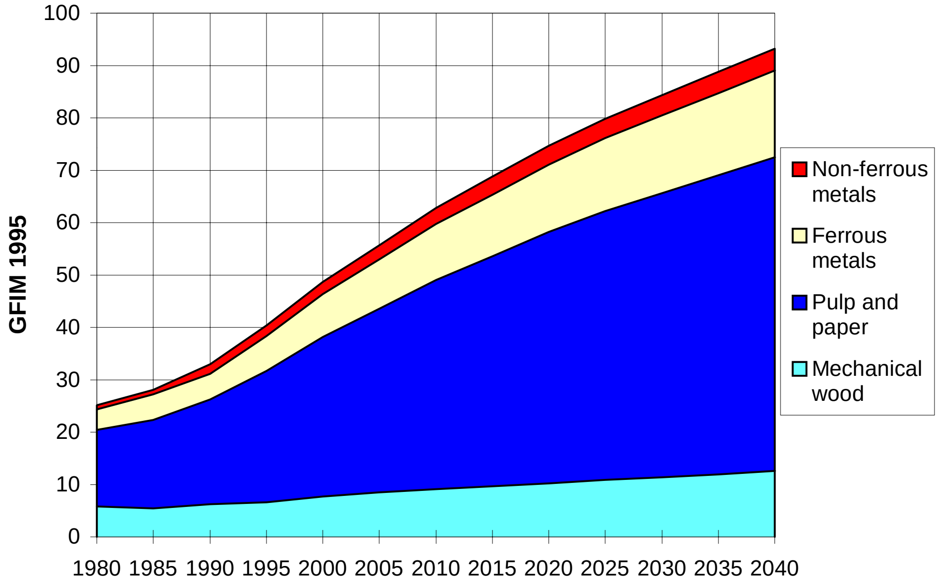

Figure B-1. Development of value added in forest and basic metal industries.

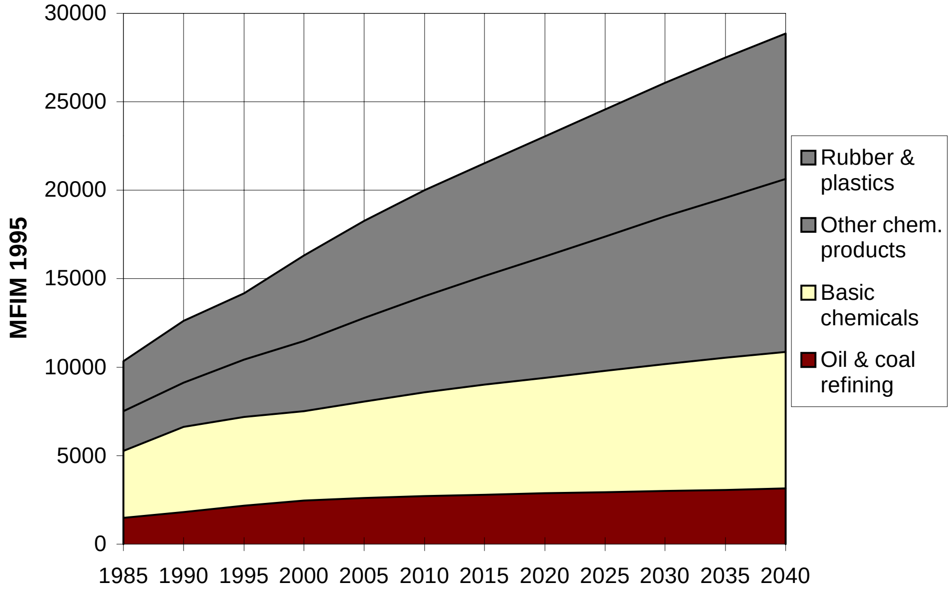

Figure B-2. Development of value added in chemical industries.

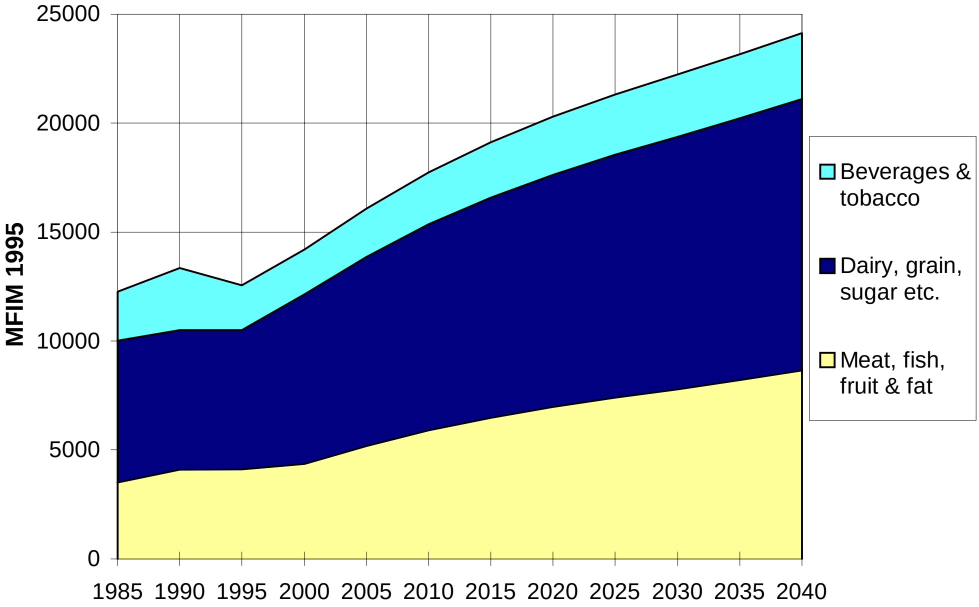

Figure B-3. Development of value added in foodstuff industries.

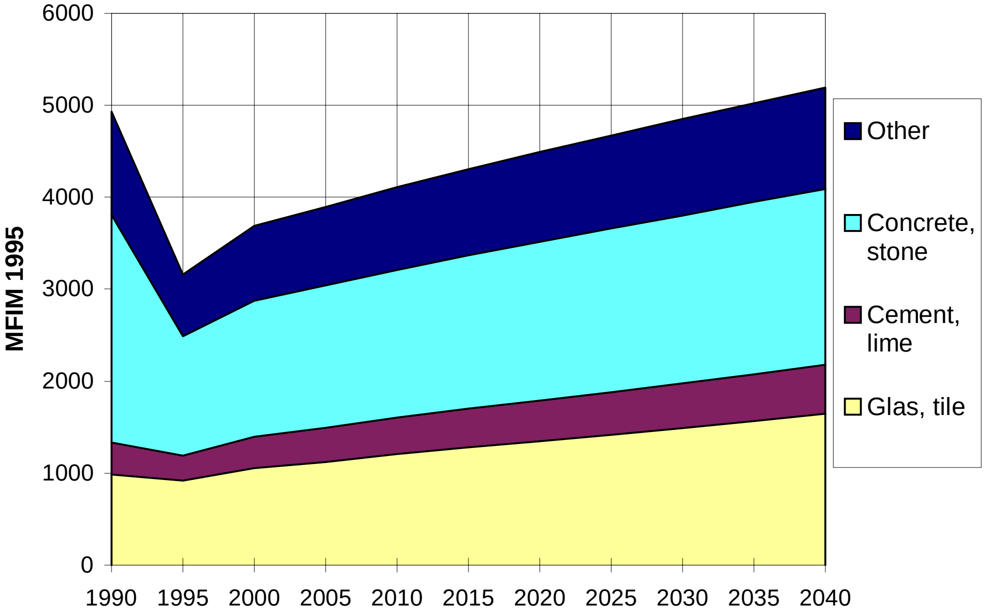

Figure B-4. Development of value added in building material industries.

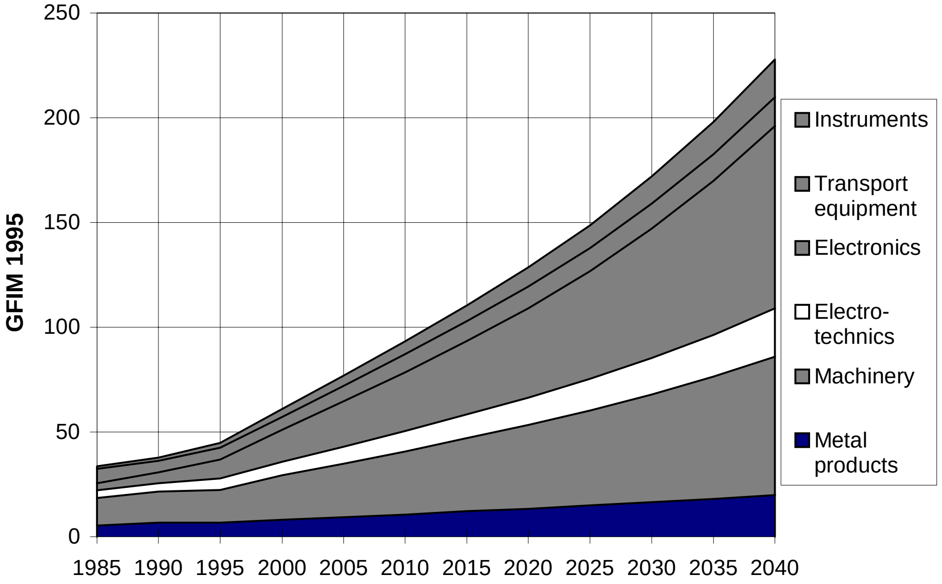

Figure B-5. Development of value added in metal products industries.

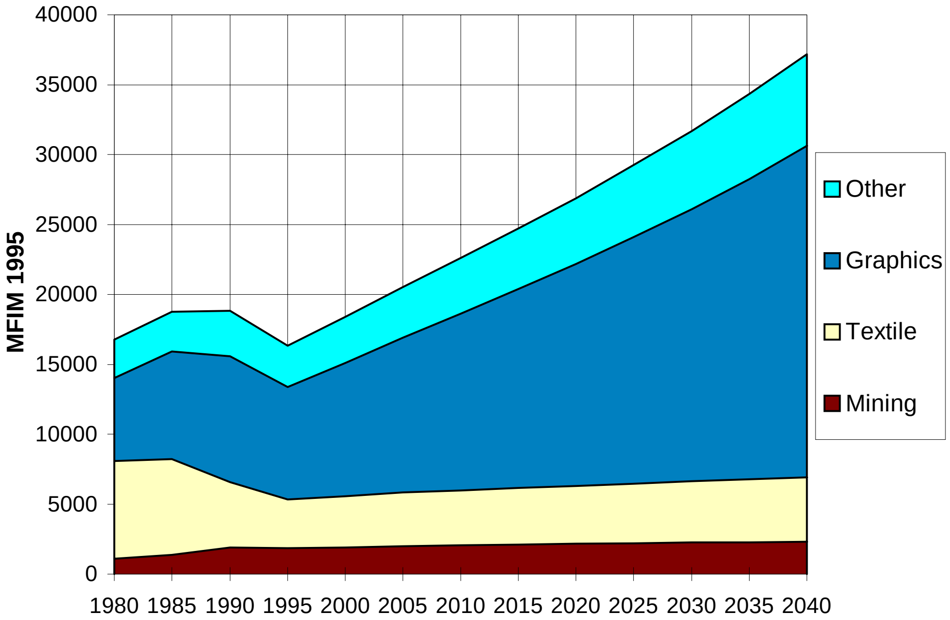

Figure B-6. Development of value added in other industries.

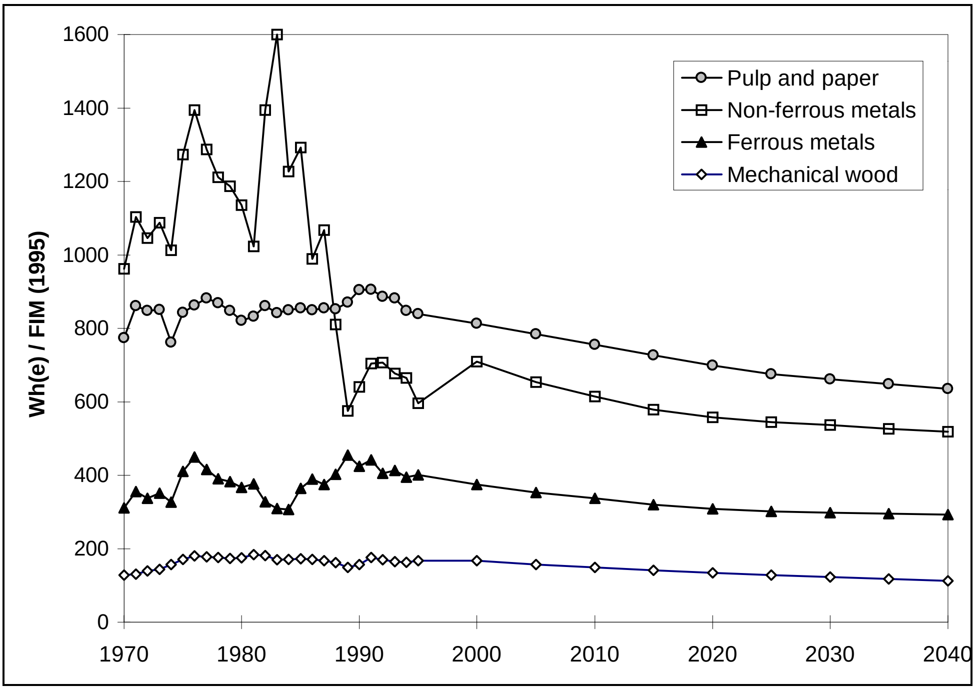

Figure B-7. Electricity consumption per value added in forest & metal industries.

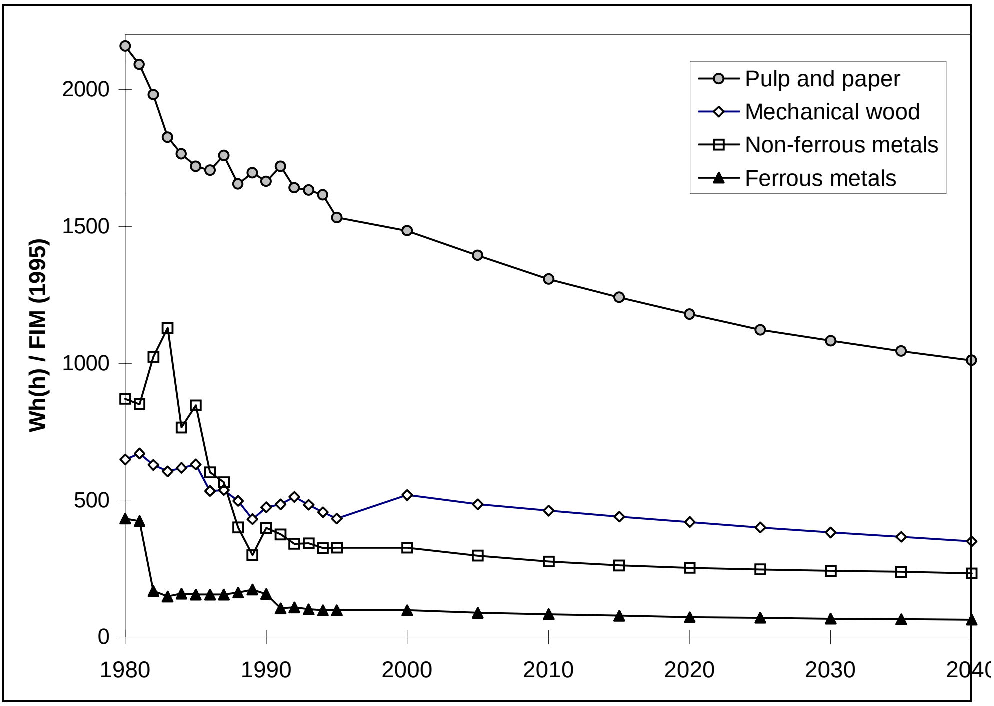

Figure B-8. Heat consumption per value added in forest & metal industries.

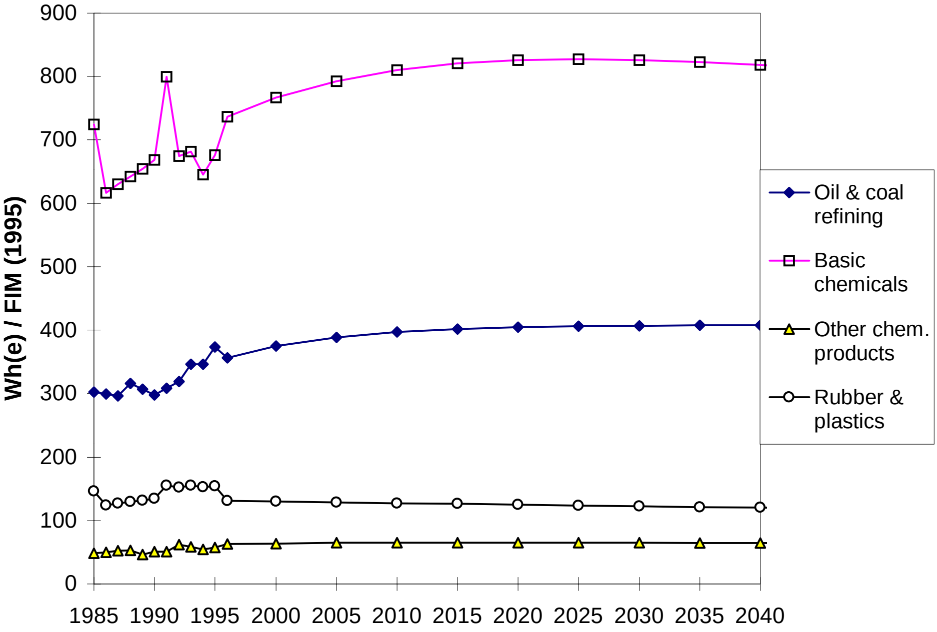

Figure B-9. Electricity consumption per value added in chemical industries.

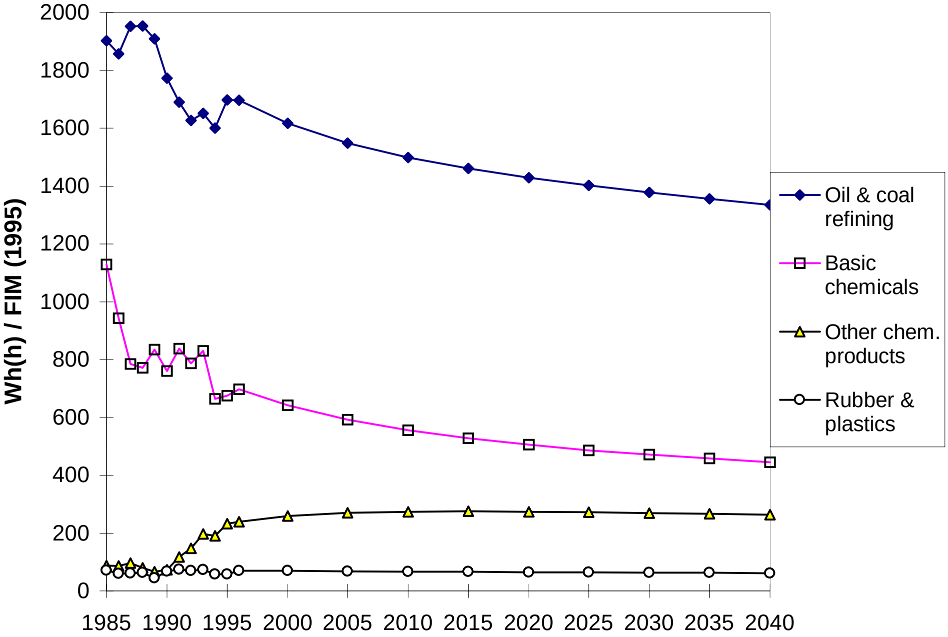

Figure B-10. Heat consumption per value added in chemical industries.

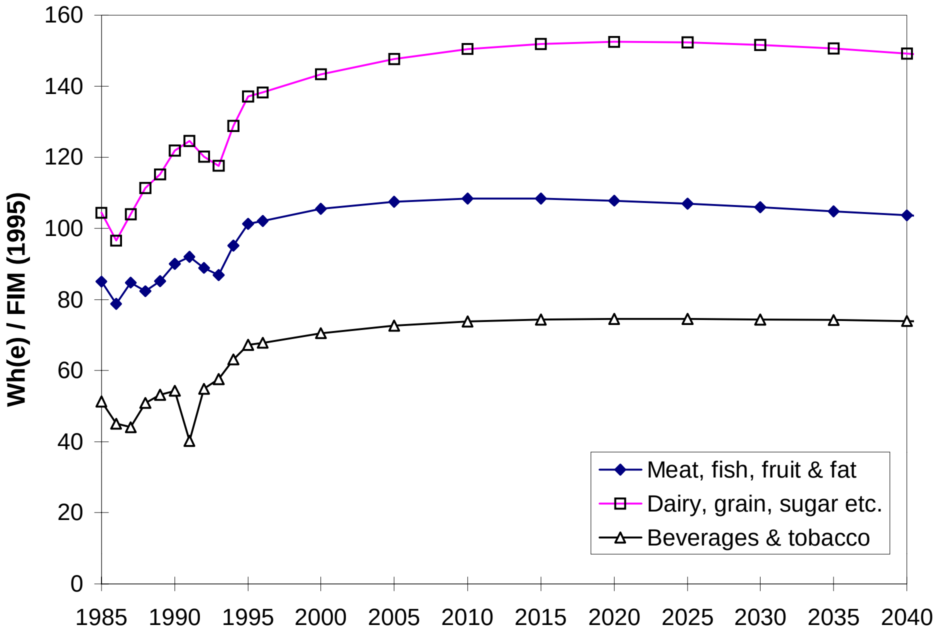

Figure B-11. Electricity consumption per value added in foodstuff industries.

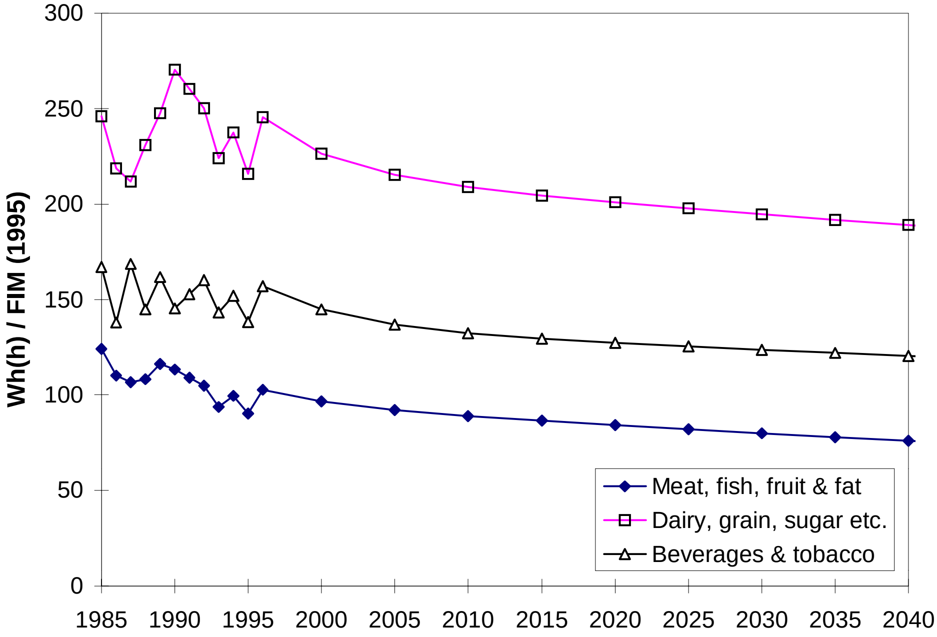

Figure B-12. Heat consumption per value added in foodstuff industries.

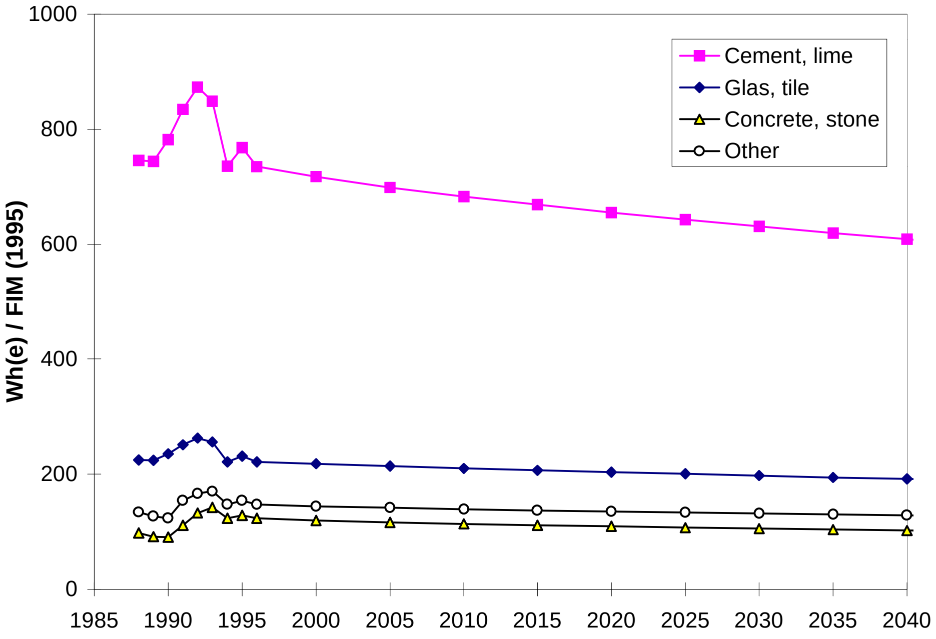

Figure B-13. Electricity use per value added in building material industries.

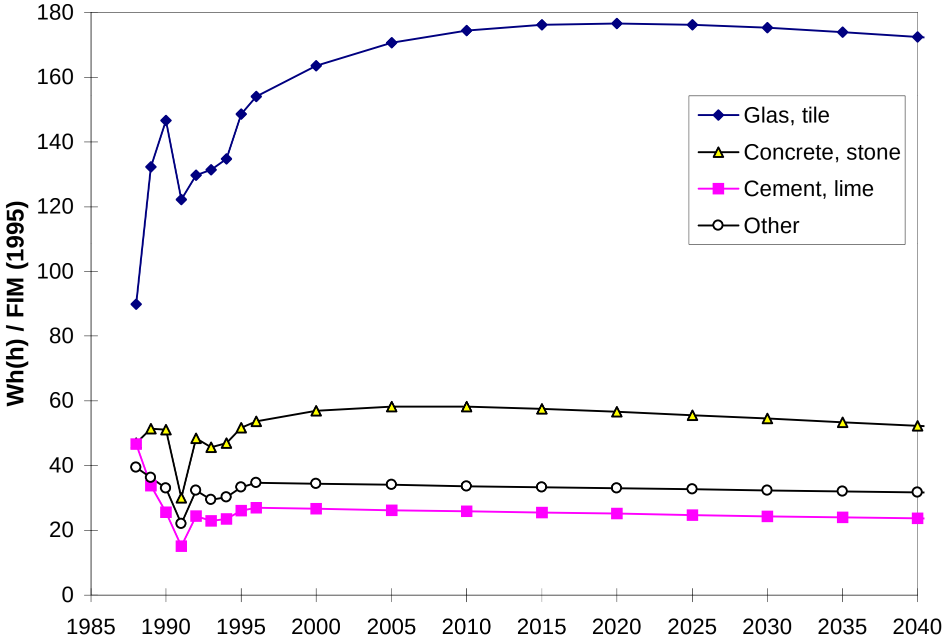

Figure B-14. Heat consumption per value added in building material industries.

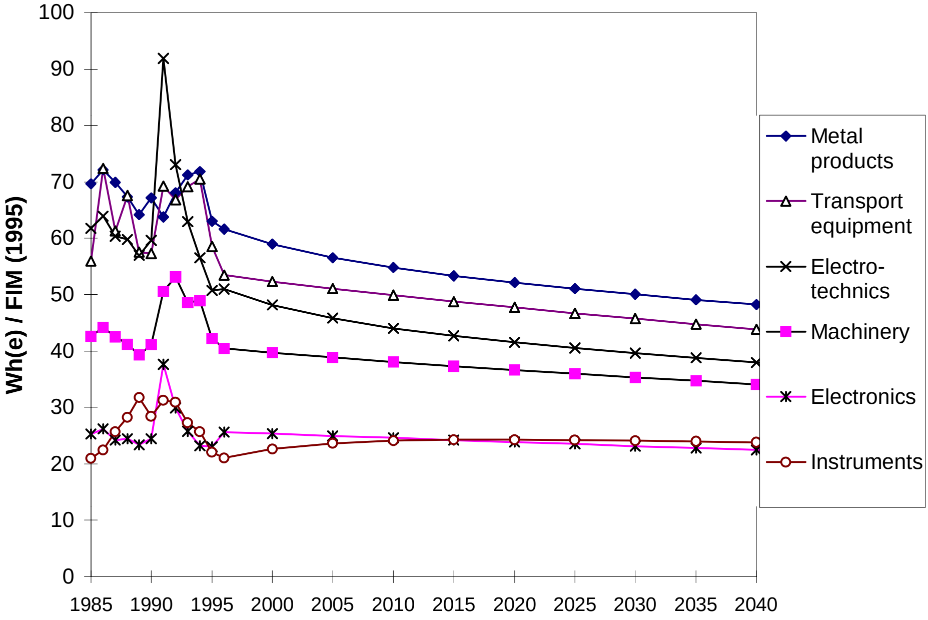

Figure B-15. Electricity use per value added in metal products industries.

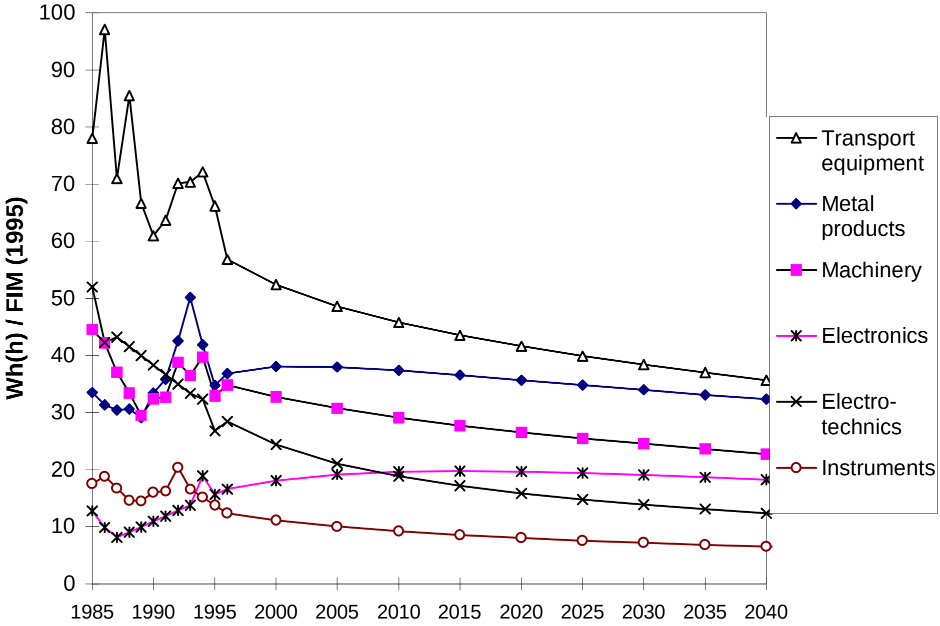

Figure B-16. Heat consumption per value added in metal products industries.

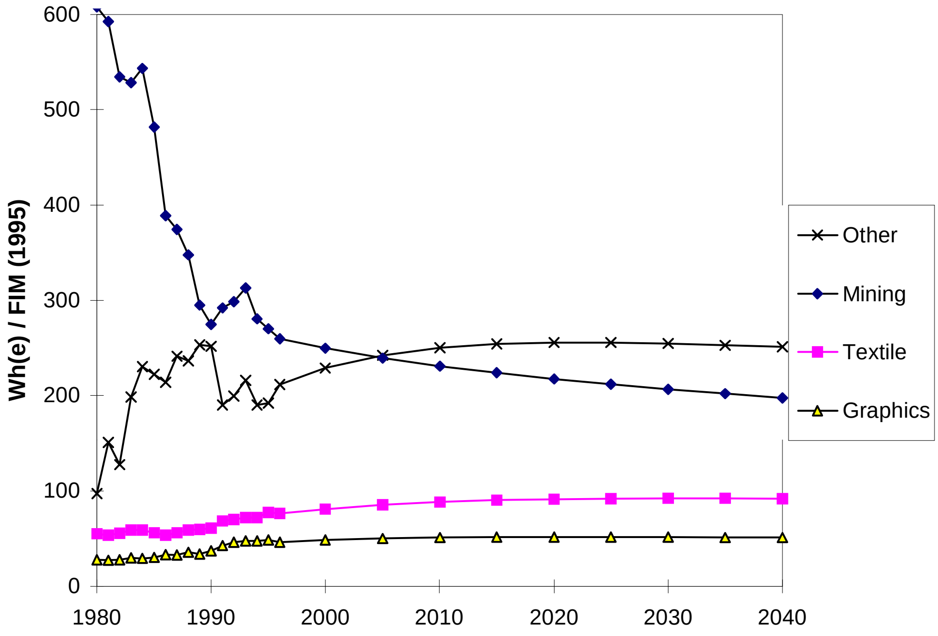

Figure B-17. Electricity consumption per value added in other industries.

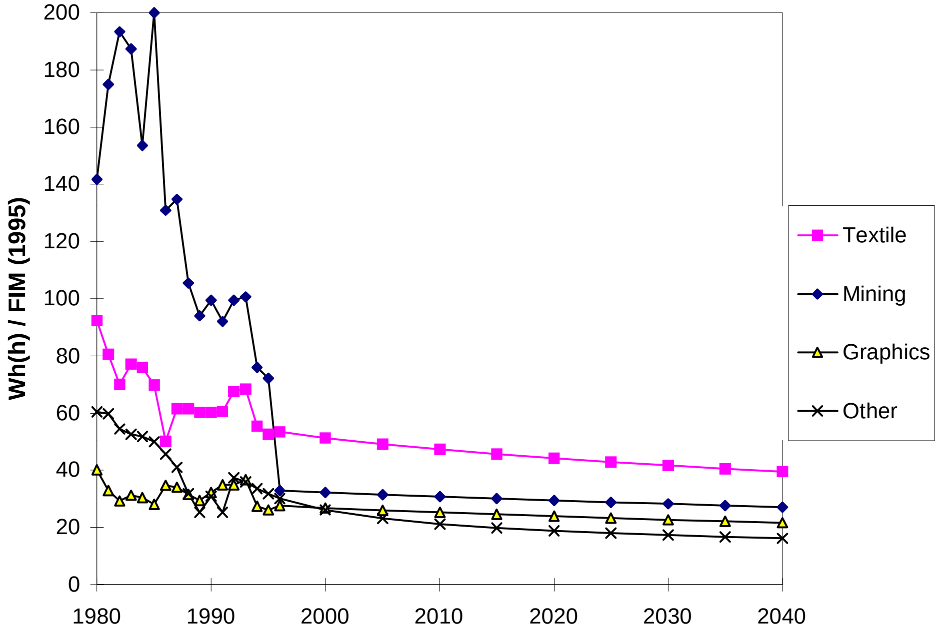

Figure B-18. Heat consumption per value added in other industries.