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The role of technology development in greenhouse gas emission reduction – Case of Finland

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Abstract

This contribution presents results from the Finnish CLIMTECH Technology programme. Projections from a total of 27 projects were used to investigate the prospects of GHG mitigation technologies in the Finnish conditions, including all emission sources and all Kyoto gases. The estimated impacts of climate change on the energy system were also taken into account in the analysis. Systematic investments in technology development were found to yield substantial benefits in the long term, by decreasing emission reduction costs and by facilitating more ambitious reduction targets. Advanced biofuel production and utilisation technologies and offshore wind power proved to have the largest potential by the 2030s. Results also indicated a clear relationship between technological development and national emission trading patterns.

1. Introduction

Control of greenhouse gas emissions can be expected to lead to considerably high costs in countries like Finland, which have cold climate, long average transportation distances and energy intensive industries. The limitation of greenhouse gas emissions can also be expected to cause changes in technologies that are used in energy production and consumption and in technologies used in other activities connected to greenhouse gas emissions. After the adoption of the Kyoto Protocol in 1997 there was a large demand for a technology programme, which could help Finnish companies in the forthcoming strategic decisions in changing operational environment. Therefore, a national technology programme, Technology and Climate Change (CLIMTECH), was run during the years 1999–2002. The overall objective of the programme was to support the mitigation of climate change by contributing to technological choices, research and development, and commercialisation of technology. Furthermore, the programme had interest in supporting the attainment of the national greenhouse gas mitigation targets.

The energy supply in Finland is very diverse. The primary energy supply is mainly based on oil, coal, gas and nuclear energy, and, to an extent exceptional among industrialised countries, on biomass fuels. In electricity supply, nuclear energy has a high share, but even larger is the total contribution of combined heat and power production in both industries and communities. Hydropower and imports of electricity have considerable shares as well. The large use of bioenergy is primarily connected to the forest industry, which produces by-products usable as fuels, such as bark, sawdust and spent pulping liquors.

Besides CO_2 from fossil fuel use, other important sources of greenhouse gas emissions in Finland are CO_2 from the production and use of fuel peat as well as N_2O from combustion processes. Agriculture causes emissions of CH_4 and N_2O, the reduction of which is relatively expensive. Emissions of CH_4 from landfills have decreased during the 1990s due to the development of improved waste management systems. The emissions of fluorinated gases of the Kyoto protocol are increasing, as they are used to replace ozone depleting gases e.g. in cooling equipment, and because cooling is increasing, especially in commercial buildings.

European Union has agreed to fulfil its emission reduction commitment of eight percent as one bubble according to Article 4 of the Kyoto Protocol. Finland’s commitment in the burden-sharing regime among the EU countries is to keep the emissions at the level of 1990. This appears to be a relatively demanding task because the emissions would increase by 20 percent without additional emission reduction measures.

Finland has also relative large industry that manufactures technology, equipment and components for energy production and use. The export of these products has increased strongly during 1990s and is presently about 6 percent of total exports, a fraction higher than in any other OECD country (Figure 1). The large energy technology exports indicate that Finland has specialised in the manufacture and export of this kind of technology in global scale. The exports consist of a wide spectrum of products like boilers, diesel engines, power electronics, and wind power plant components such as generators, gears and blade materials.

As the deployment of new technologies takes years or even decades, and as the lifetimes of many investments of the energy production and consumption system are long, the time scale of the studies in the CLIMTECH programme extended to 2030. This time scale also enabled the programme to bring into focus such technologies whose potential is insignificant over the first commitment period of the Kyoto Protocol, but might be substantial in fulfilling the subsequent commitments.

In the CLIMTECH Programme technologies were analysed against an overall scenario of emission limitation in which the technological and economic potentials were assessed. Altogether the programme consisted of 27 projects that were implemented by seven research institutes or universities and by eight companies. The projects were divided into six main subject areas:

1. Renewable energy sources and distributed energy production,
2. Energy efficiency and industry,
3. Non-CO_2 greenhouse gases,
4. Capture and utilisation of CO_2,
5. Development of models and systems,
6. Commercialisation.

The Programme included also a project that made assessments about the impacts of changing climate on the energy economy in Finland.

The objective of this paper is to present the main results of a scenario study made under the CLIMTECH Programme. The purpose of the study was to investigate the role of technology development in the abatement of greenhouse gas emissions and estimate the costs of emission control in Finland. Practically all emission sources and gases controlled by the Kyoto Protocol were considered in the study. The technologies with the largest and most cost-effective emission reduction potential were identified.

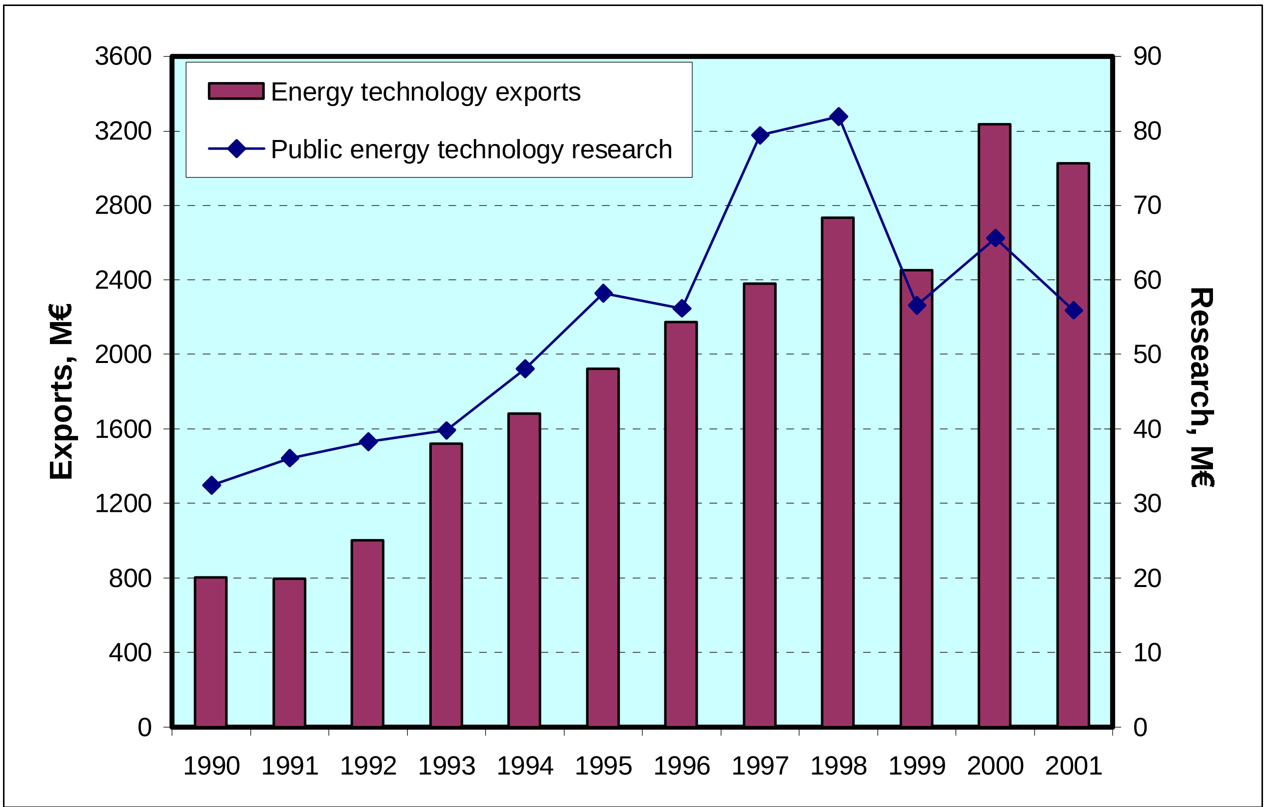

Figure 1. Development of energy technology exports and public energy technology research budgets in Finland between 1990 and 2001 (Source: Official national statistics & IEA R&D statistics).

2. Modeling methodology

The modeling methodology used in the scenario study is based on the technology-rich bottom-up energy system model EFOM. Like the widely known MARKAL model, EFOM is a dynamic linear programming model of energy systems. The model was first developed in the early 1980s under the European Commission for traditional energy planning (van der Voort et al. 1984). However, over the years the modeling system has undergone substantial development, in particular concerning the environmental impacts of energy production and energy use. Combined with the MARKAL approach, the methodology continues to be developed and refined under the IEA Energy Technology Systems Analysis Programme (ETSAP). The new TIMES modeling framework developed within ETSAP (The Integrated MARKAL-EFOM System) is the evolutionary replacement for both MARKAL and EFOM, with many improvements in methodology and wider application areas ranging from local energy planning to global modeling (Goldstein & Greening 1999).

These models can answer a number of different policy and planning questions. The widest current applications are related to the analysis of policies designed to reduce greenhouse gas emissions from energy and materials consumption. Since the framework depicts individual technologies, it is particularly useful for evaluating policies that promote the use of technologies of greater efficiency in energy or materials, or the development and use of new technologies. Aggregate modeling frameworks (e.g. macroeconomic models) generally lack such capacity. Considering that policies affecting technology choice represent one of the primary means for reducing GHG emissions, this is an important strength of the methodology.

The model has a modular structure consisting of identifiable sub-sectors of the energy system, as depicted in Figure 2. A user-defined network describes the various interconnections and transformations between primary supplies, conversion and processing, distribution and end-use demand for energy services. The demand for energy services may be disaggregated by sector (i.e., residential, manufacturing, transportation, and commercial) and by specific functions within a sector (e.g., residential air conditioning, heating, lighting, hot water, etc.). The model version

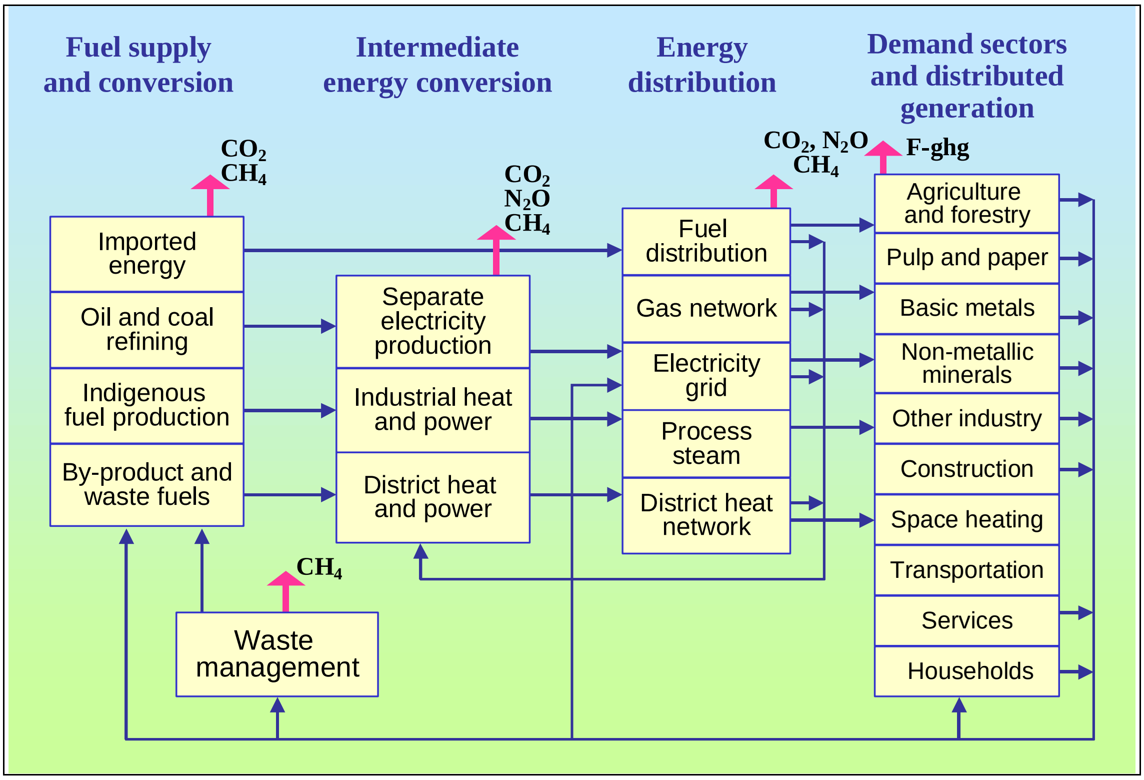

Figure 2. Overview of the modular structure of the energy system model.

currently in use at VTT is a single-nation model for Finland (Lehtilä & Pirilä 1996). Exports and imports of various energy carriers are accounted for by using supply and demand curves, which are specified by exogenous parameters. The new TIMES-version of the model commissioned in 2003 is planned to be later expanded into a multinational version covering all Nordic countries.

Mathematically, the model is a quasi-dynamic linear optimization model. By using the model, the development of the energy system is typically studied over a time horizon of up to 30–50 years. The user defines the costs of resources and technology, technical characteristics (e.g. conversion efficiencies), and demands for energy services. The optimization selects from each of the sources, energy carriers, and transformation technologies to produce the least-cost solution subject to a variety of constraints. As a result of this integrated approach, supply-side technologies are matched up with energy service demands. The specification of new technologies allows the user to explore the effects of these choices on total system costs, changes in fuel and technology mix, and the levels of greenhouse gases and other emissions. Therefore, the model is highly useful for understanding the role of technology in climate change mitigation and other energy system planning issues.

A variety of different restraints may be applied to the least-cost solution. In addition to constraints related to a consistent representation of the energy system, various environmental standards and policy issues can be described by specifying additional constraints or market-based economic instruments, such as taxes on energy and emissions. Greenhouse gas emissions may be examined in several ways, including sectoral or system-wide limits on annual emissions and limits on cumulative emissions or incremental radiative forcing over time. Alternatively, the imposition of a carbon tax or an emission permit trading system can be modeled when desired. For each combination of policy constraints and instruments, the model generates a least-cost solution with a different configuration of future technology.

The solution of the EFOM model may be interpreted as competitive market equilibrium for energy markets, where energy demands are fixed scenarios. The final demands are thus not elastic, although final energy consumption is, of course, quite flexible through end-use technology choices. However, a more complete representation of market behavior would include the endogenous determination of price sensitive useful energy demand jointly with price sensitive supplies of energy. Such a genuine partial equilibrium approach is supported by the new TIMES modeling framework, and it represents an important refinement to the methodology used in the EFOM model.

The energy system model includes practically all emission sources of the greenhouse gases included in the Kyoto protocol, i.e. carbon dioxide, methane, nitrous oxide and fluorinated gases. Concerning the non-CO_2 emissions, approximately 4% of the total Finnish greenhouse gas emissions, corresponding to about 25% of all non-CO_2 emissions, consists of methane from waste management. Agriculture is a roughly equally important source of methane emissions and produces about 50% of N_2O emissions. In order to take into account the technical options for reducing these emissions, modules for waste management and agriculture are included in the model. As in waste management methane is released in the slow degradation process of organic waste at landfill sites, also a fully dynamic description of the degradation process is included in the model.

The introduction of agricultural and waste management modules represent the first steps from an energy planning model into an integrated framework for long-term natural resource planning. At a later stage, a dynamic forestry module could be added in order to include long-term impacts of forest management options on greenhouse gas balances and bioenergy resources.

3. Scenarios studied

In order to make an integrated assessment of the role of advanced and new technologies in the future energy system of Finland, the technology projections made in the individual studies of the CLIMTECH Programme were pulled together and compiled into the technology database of the energy system model. The coordination team of the Programme specified the scenarios to be studied. The total study horizon of the scenarios was chosen to be 2000–2040, of which the focus was set on the years 2010, 2020 and 2030. The main interest was in the longer term beyond the Kyoto period. Two possible future development paths were characterized for the scenarios:

- 'Conventional' development: International measures for climate change mitigation evolve slowly. There is no major push for the development and commercialisation of cleaner technologies. As a result, the penetration of new energy technologies is slow and depends highly on economic policy instruments.
- 'Optimistic' development: Accelerated climate change mitigation measures lead to boosted development and employment of cleaner technologies, both in the international context and within Finland. Increased funding for both R&D and promotion of technologies reducing emissions is thereby implicitly assumed.

In general, it was assumed in the scenarios that new and stricter emission reduction targets would be set after the Kyoto period. For comparison, however, a 'Kyoto' scenario was also calculated where only the Kyoto emission target was assumed to remain in force. Additionally, a baseline scenario was calculated as a reference for the comparison of total costs and emissions. In all but the baseline scenario, emission reduction targets were assumed both for the Kyoto period in 2008–2012 and for the year 2030. The abatement levels studied for the year 2030 were 0%, –10%, –20% and –30% from the 1990 level. All the six greenhouse gases included in the Kyoto protocol were considered in the scenarios. The energy system model was used to find the least-cost allocations of greenhouse gas emission reductions in the scenarios. In addition, the impacts of GHG reduction targets on other air pollutant emissions (SO_2, NO_X, NH_3 and particulates) were calculated as well.

The policy instruments that were used to drive the emissions to the targets were based both on the current tax and subsidy system effective in Finland, and on a hypothetical general tax on all GHG emissions in CO_2 equivalent terms (using the GWP-100 index). The current tax structure was assumed to prevail in all scenarios until 2010. However, in all other but the Kyoto scenario the current system was assumed to be gradually replaced by the general tax on GWP between 2010 and 2030. The use of a hypothetical general emission tax was considered necessary for an unbiased cost-efficiency assessment with respect to emission reduction. Additionally, the effects of carbon

Table 1. Summary of the differences in the main scenario assumptions.

Scenario	Short name	Technology development	GHG emission reduction in 2030		Basis of policy instruments	
			Base	Variants	by 2010	by 2030
Kyoto	Kyoto	conventional	0%	–	current taxes and subsidies	current taxes and subsidies
Conventional development	Conv.	conventional	–20%	–10%, –30%	current taxes and subsidies	tax on GWP, all sectors
Conventional, CO_2 trade	Conv.-ET	conventional	–20%	–	current taxes and subsidies	tax on non-tradable GWP
Optimistic development	Opt.	boosted	–20%	–10%, –30%	current taxes and subsidies	tax on GWP, all sectors
Optimistic, CO_2 trade	Opt.-ET	boosted	–20%	–	current taxes and subsidies	tax on non-tradable GWP

dioxide emission trading were considered in a few scenario variants. In these scenarios emission trading was assumed to be applicable to the CO_2 emissions of large-scale energy production and industries only, in accordance with the EU directive on CO_2 trade. In the trading scenarios all the tax-based policy instruments were removed from the emission sources involved in trading.

The general economic and demographic assumptions used in the study were mostly based on those used in the National Climate Strategy (Government 2001). The economic projections are based on a smooth and slowly retarding growth throughout the time horizon. As nuclear power technologies were not considered within the CLIMTECH Programme, the co-ordination team decided to restrict additional nuclear power in the scenarios to the currently planned single new unit only.

The technology data for the scenarios were taken mainly from the various CLIMTECH studies (Soimakallio & Savolainen 2002). For technologies not included in the programme, estimates were also taken from a recent Energy Visions 2030 study made at VTT (Kara et al. 2001) and other earlier domestic and international studies. Projections for the development of the most important technology-specific parameters, such as efficiencies and investment costs, were derived for the two different future pathways of technology development. In the Conventional scenario, technical and economic parameters develop at normal rates comparable to historical development, while in the Optimistic scenarios the performance figures improve at rates that could be reached, according to the CLIMTECH studies, with systematic and intensive investments in research and development.

Some examples of the technology projections used in the scenario study are illustrated Figure 3. The examples show the development of investment costs and electrical efficiency of six different electricity generation technologies in new installations. However, for solar and wind technologies, annual capacity factor is shown instead of efficiency. The ranges between the Conventional and Optimistic projections are shown for both parameters in the figure.

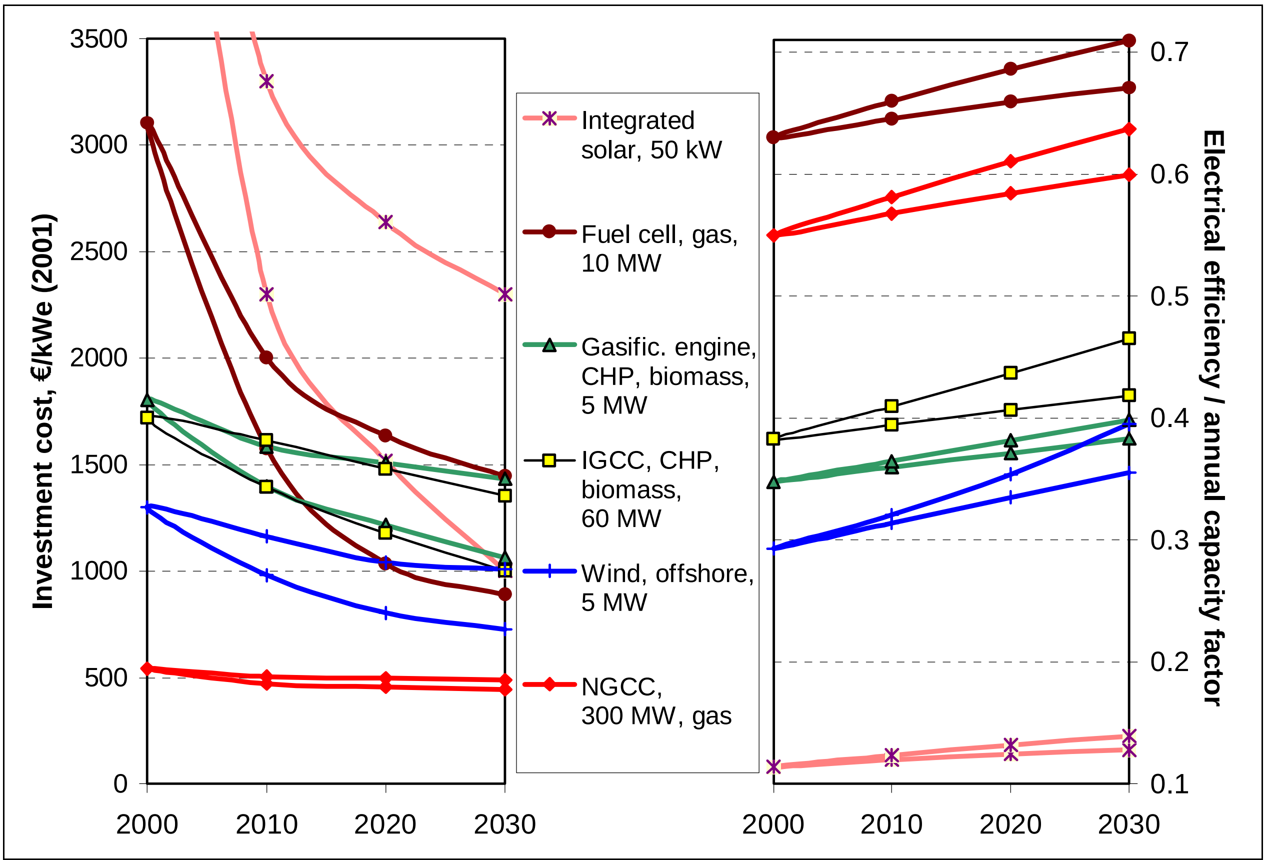

Figure 3. Examples of ranges in technology projections for new electricity generation plants. For wind and solar, development of annual capacity factor is shown instead of electrical efficiency.

4. Projections for climate change impacts

Climate change can have significant impacts on energy resources and on the energy production infrastructure, on the competitiveness of individual energy sources and thus on greenhouse gas emissions as well. In the scenario study of the CLIMTECH programme, the plausible impacts of climate change were taken into account on the basis of recent IPCC scenarios. A project consortium led by the Finnish Meteorological Institute investigated the impacts of estimated climate change on energy production in the Finnish conditions by the 2030s (Tammelin et al. 2002).

The study concentrated on changes in heating energy consumption, hydropower, the climatological potential of peat production, biomass growth and wind energy. The assessments were based on monthly temperature, precipitation and wind data from the Hadley Centre HadCM3 climate model (Gordon et al. 2000, Pope et al. 2000) simulating the recent IPCC A2 and B2 scenarios (Nakicenovic 2000). For changes in wind speeds, results were also available from the more detailed SMHI regional model. Changes in hydropower availability were studied with watershed models of the Finnish Environment Institute (Vehviläinen & Huttunen 1997).

Most important changes for energy production in Finland were found to occur in hydropower availability. Increased wintertime precipitation and more frequent snowmelt periods were estimated to increase the total annual hydropower production (assuming the present infrastructure) by 7–11% in the A2 and B2 scenarios. These new estimates are considerably high compared to earlier national and joint Nordic studies where the increase in hydropower has been projected to be 2.5–4%, (Kuivalainen et al. 1996, Sælthun et al. 1998). Wind power potential was estimated to increase by 4–10% in the A2 scenario and by 0–8% in the B2 scenario, depending on location. The largest increases occurred at offshore locations. Specific heating energy consumption was projected to decrease by 10–14% by the 2030s. Warmer summer periods were estimated to enhance the production potential of peat by about 17–24% through enabling more frequent collection of peat at the production areas. Estimates of changes in biomass growth and in the availability of bioenergy were based on earlier studies, indicating a growth of about 20% in the annual increment of forests, and an increase of 15% in the logging potential.

A summary of the estimated impacts of climate change is presented in Table 2, together with the assumptions adopted for the CLIMTECH scenarios. As shown in the table, due to the large uncertainties involved in the projections for forest growth, no climate impacts on the potential of biomass production were taken into account in the scenarios. The favourable impact on peat production was taken into account by assuming a small decrease in production costs. For all other impacts, the assumptions used in the scenarios were well within the ranges estimated by the study. Concerning hydropower, the projected change in seasonal distribution was also taken into account.

Table 2. Influence of projected climate change on energy production and specific heating requirements between 1961–1990 and 2021–2050.

Scope of influence	Estimated Influence of climate change [1]	Influence assumed in the scenarios
Potential for wood biomass production	15%	0%
Potential for milled peat production	17–24%	3% decrease in costs
Runoff for hydropower production	6.6–11.2%	8.7%
Potential of coastal wind power	3–8%	7%
Potential of offshore and arctic wind power	3–10%	5%
Specific consumption of space heat	– 10–14%	– 12%
Thermal efficiency of condensing power	– 0.25 – 1 %	– 0.25–1%

[1] Source: Tammelin et al. (2002)

5. Results from scenarios

5.1 Primary energy supply

Economic growth tends to imply increased use of energy in society, which in turn gives rise to larger emissions and pressure on ecosystems. As in the future growth can still be expected to be the key factor driving energy demand, decoupling economic growth from the environmental impacts of energy use will become important. The link between total primary energy consumption and GDP was in Finland quite strong still in the 1980s, but during the past decade a first clear indication of decoupling could be seen. Energy intensities fell rapidly during 1994–2000 due to efficiency improvements and structural changes, with the IT industries and service sector becoming increasingly important. The average decrease in total energy intensity was as high as 3.5% per annum.

According to recent baseline projections made in Finland, the total primary energy consumption will increase to slightly over 1500 PJ in 2010, i.e. about 1.5% per annum between 2000 and 2010. The scenario results indicate that, due to the measures needed to reach the Kyoto emission target, the growth will be reduced to about 1.2% per annum. Without further emission targets, total energy consumption would continue to increase slowly until 2030. However, in the scenarios with the 20% emission reduction target by 2030, the growth in primary energy consumption stagnates, or even turns into a decline. Decoupling of primary energy consumption from economic growth thus appears to be fully achievable in Finland by 2020, as illustrated in Figure 4.

The most cost-effective technology choices related to emission reductions are clearly reflected in the development of total primary energy consumption. The tighter the emission goal in 2030 is, the more renewable energy sources are utilized. In the year 2030, the percentage of renewables in primary energy consumption is 28% in the Kyoto scenario, 34% in the Conventional scenario, and even 37% in the Optimistic scenario, compared with the 25% contribution in 2000. Of the various forms of renewable energy, the use of bioenergy increases most in total energy supply. The use of

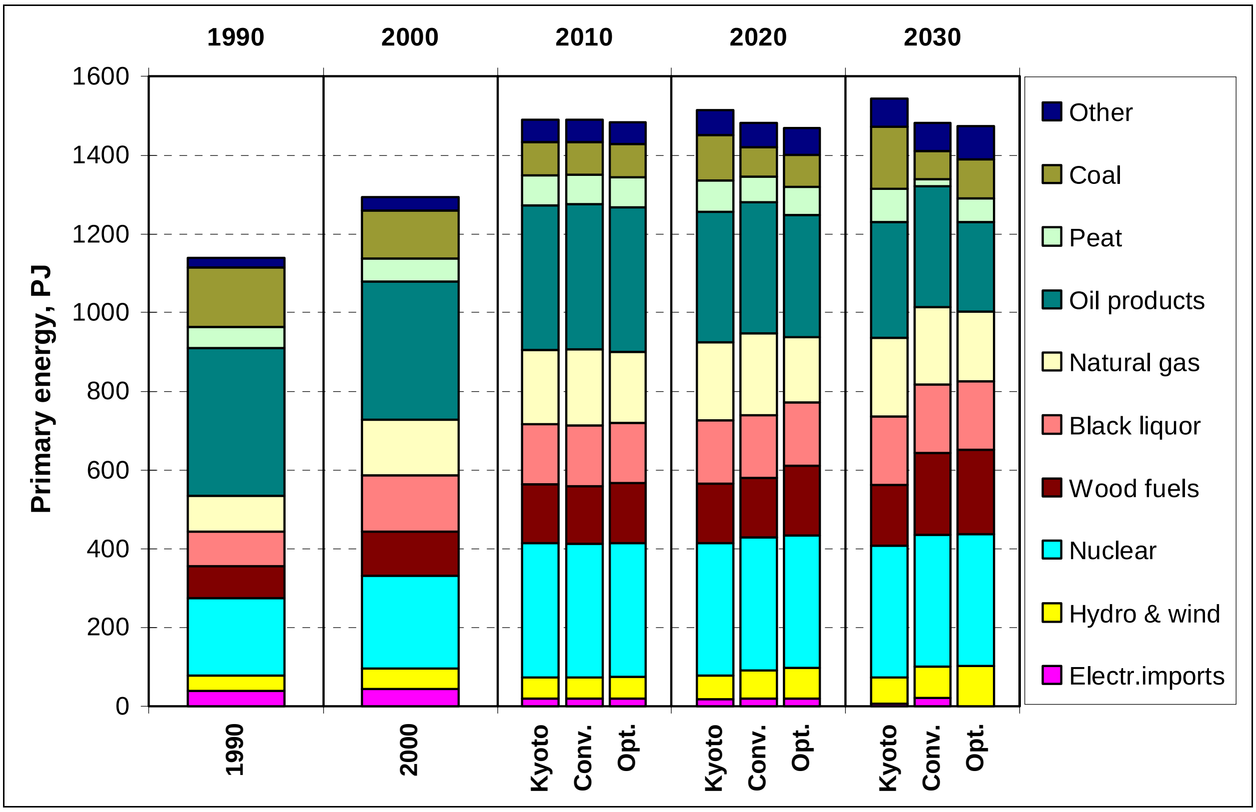

Figure 4. Primary energy supply by energy source in the Kyoto, Conventional and Optimistic scenarios between 1990 and 2030.

wood fuels grows by 20–70% between 2000 and 2030. In addition, waste-derived fuels as well as wind power and hydropower would be utilised significantly compared to the current level.

The combined use of fossil fuels and peat remains approximately stable in the Kyoto scenario, while it decreases in the scenarios requiring stricter emission reductions beyond 2010. Although the consumption of natural gas increases in all three scenarios, the relatively rapid increase in the price of gas reverses consumption after 2020. Particularly notable is the decrease in the use of oil in the Optimistic scenario after 2020, which is largely due to the revolution in road vehicle technology.

Just over half of the current total bioenergy supply is covered by black liquor. Most of the other use of bioenergy consists of different types of solid wood fuels, as depicted in Figure 5. Integrating fuel production with final fellings or thinnings can significantly increase the economic potential of wood fuel utilisation. Bioenergy sources and forms of use may diversify considerably in the future along with the production of recycled fuels, agrobiomass and pyrolysis oil as well as ethanol as a component of transport fuel. Bioethanol was assumed to be imported in the scenarios, whereas only domestic sources were considered for other bioenergy fuels.

According to the results, production technologies of pyrolysis oil and recycled fuels are of central importance in the emission reductions related to bioenergy utilization. The development of technologies for the production and use of pyrolysis oil thus appears to be a promising option in terms of both emission reductions and new business prospects in energy technology (Sipilä et al 1999).

5.2 Power and heat production

Technology choices in electricity generation have a large impact on carbon dioxide emissions. The most significant modifications in the basic structure of electricity supply are associated with separate electricity production and electricity imports, as shown in Figure 6. The more stringent the emission targets, the less will be the production of conventional condensing power. The share of combined heat and power production increases in all scenarios but may stabilise at a level of 40%. The generation of wind power increases to about 1 TWh by 2010 and to 3–12.5 TWh by 2030. The

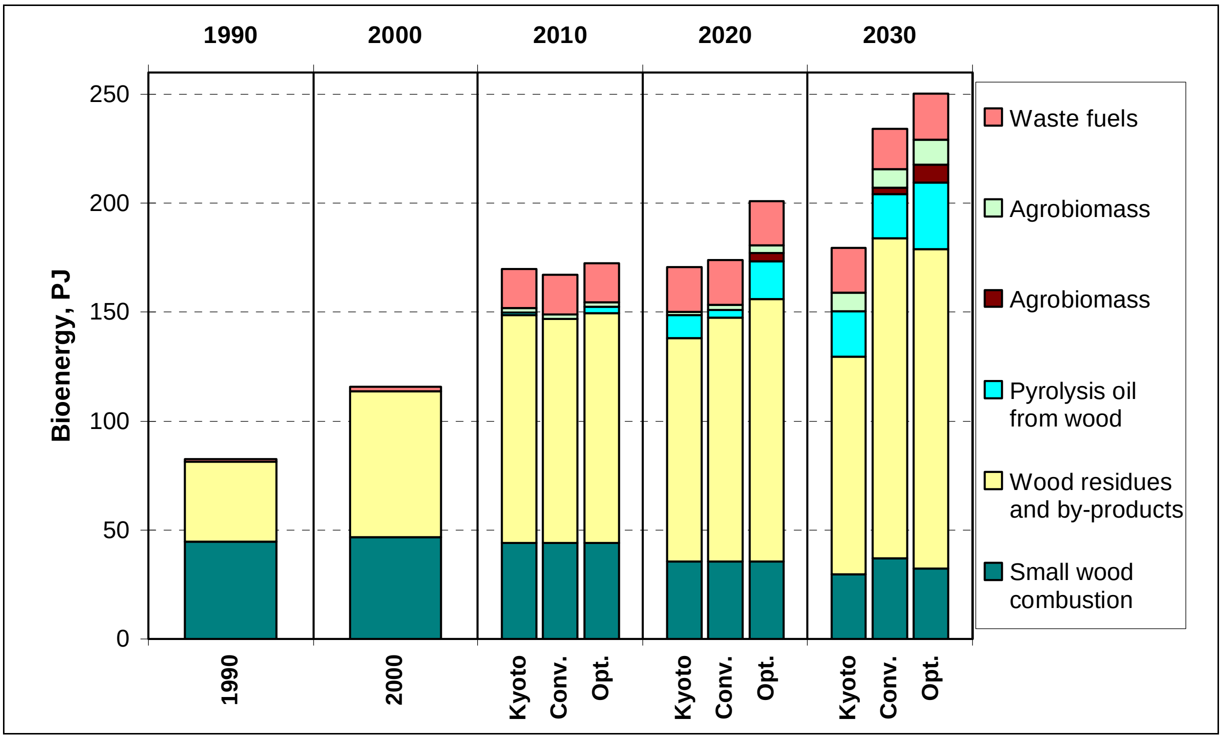

Figure 5. Structure of bioenergy supply in the Kyoto, Conventional and Optimistic scenarios between 1990 and 2030, excluding waste liquors from pulping.

optimistic scenario produces by far the largest expansions in wind power, due to the declining production costs of advanced offshore wind turbines. Development of wind power systems appears to be one of the most significant individual technological options that allow emission reductions with moderate costs in the medium-long term to 2030. In the Optimistic scenario, also photovoltaics integrated into buildings would gain notable market share around 2030.

According to the results, existing technologies based on steam and gas turbines in combined heat and power plants will continue to play a major role alongside with newer technologies until 2030. The natural gas combined cycle technology would be the most significant individual technology in district heat generation, especially in the case of conventional development. Biofuel gasifiers installed in large steam turbine plants would become economically attractive by 2010. By the year 2020 integrated gasification gas turbines and small gasification engines in distributed generation turn out to be competitive. In addition, also natural gas combined cycle power plants may be equipped by bio-gasifiers. On the whole, gasification technologies appear to have very significant potential in the efficient and flexible use of solid biofuels both in CHP production and in small heating plants, but need still active further development for improved economics.

The production of pyrolysis oil could open up considerable potential to reduce oil consumption in district heating. With rapid development, bio-oil would become competitive by 2010 and could have a major market share by 2020. In order realize the market prospects depicted by the optimistic scenario, substantial development is however required in both pyrolysis and boiler technology.

In industrial cogeneration, the soda-recovery boiler coupled with a steam turbine still remains the most significant individual generation technology by 2030. The power-to-heat ratios can, however, be considerably improved in new soda-recovery boilers compared with current units. Another promising alternative for an even much more efficient use of black liquor is the gasification combined cycle technology, which becomes highly competitive in the optimistic scenario and attains a major market share by 2030. Wood-based as well as refinery oil based industrial IGCC plants become competitive in both Conventional and Optimistic scenarios.

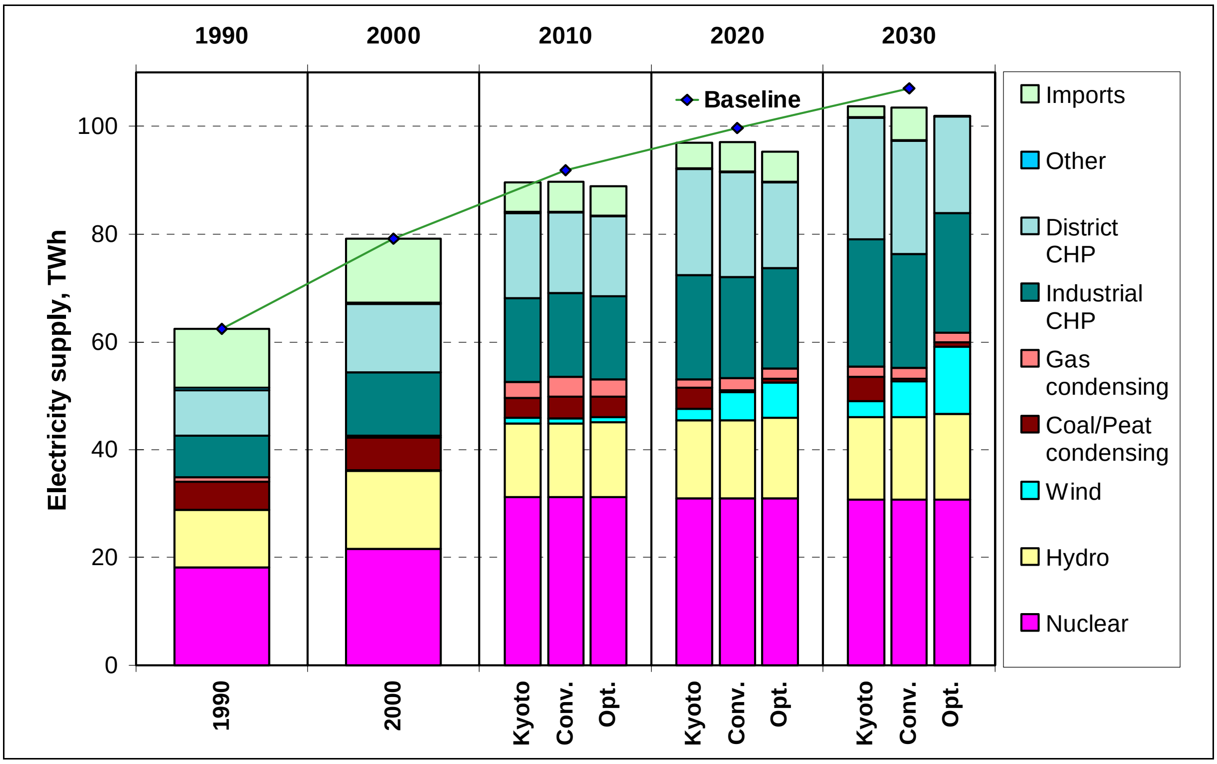

Figure 6. Development of the structure of total electricity supply by in the Kyoto, Conventional and Optimistic scenarios between 1990 and 2030.

5.3 Technology deployment in other sectors

In the analysis concerning heating energy demand, both climate change impacts and non-climatic effects were considered. Specific heat demand in both new and old buildings is projected to decrease not only due to global warming, but also through demographic changes in population distribution, stricter building codes and subsidies for renovation. Consequently, the total consumption of space heat will decrease, despite the fact that building stock is projected to increase considerably. According to the results, the market shares of district heating, biofuel-based heating and electric heating (incl. heat pumps) would all grow, while oil-based heating declines. Development of automatically fed stoker-boilers, pellet fireplaces, and particularly to pyrolysis oil boilers has a considerable role in reducing the use of mineral oil in order to abate emissions. In the case of optimistic development, solar heating gains access to the market on a relatively broad scale in 2030.

The forest industry, and especially energy-intensive mechanical pulping, is a significant user of electric power in Finland. Through the implementation of biotechnological methods like the fungal pre-treatment of chips (biopulping) and enzyme-aided refining, electricity consumption can be reduced. The scenario results showed that enzyme-aided refining was quite competitive compared with alternative methods, and it would already reach maximal penetration of use in the conventional scenario (Figure 7). Bio-pulping, which is technically more difficult to control and also more expensive from the point of view of investment and operation, would be largely adopted in the Optimistic scenario by 2020. An additional life-cycle study confirmed that the biotechnical methods reduce total emissions of greenhouse gases over the full production chain (Kallioinen et al. 2003).

Concerning other technologies for industrial end-use of energy, the CLIMTECH studies produced no new technology projections. Therefore, in the scenarios the technology characterization for all other industrial end-uses was based on earlier studies. On the basis of those earlier data, the results show considerable conservation potential in the process steam consumption of heavy industries. Other notable cost-efficient technical options within the industrial sectors include e.g. N_2O reduction in nitric acid production, and the increased use of blast furnace slag in cement manufacturing.

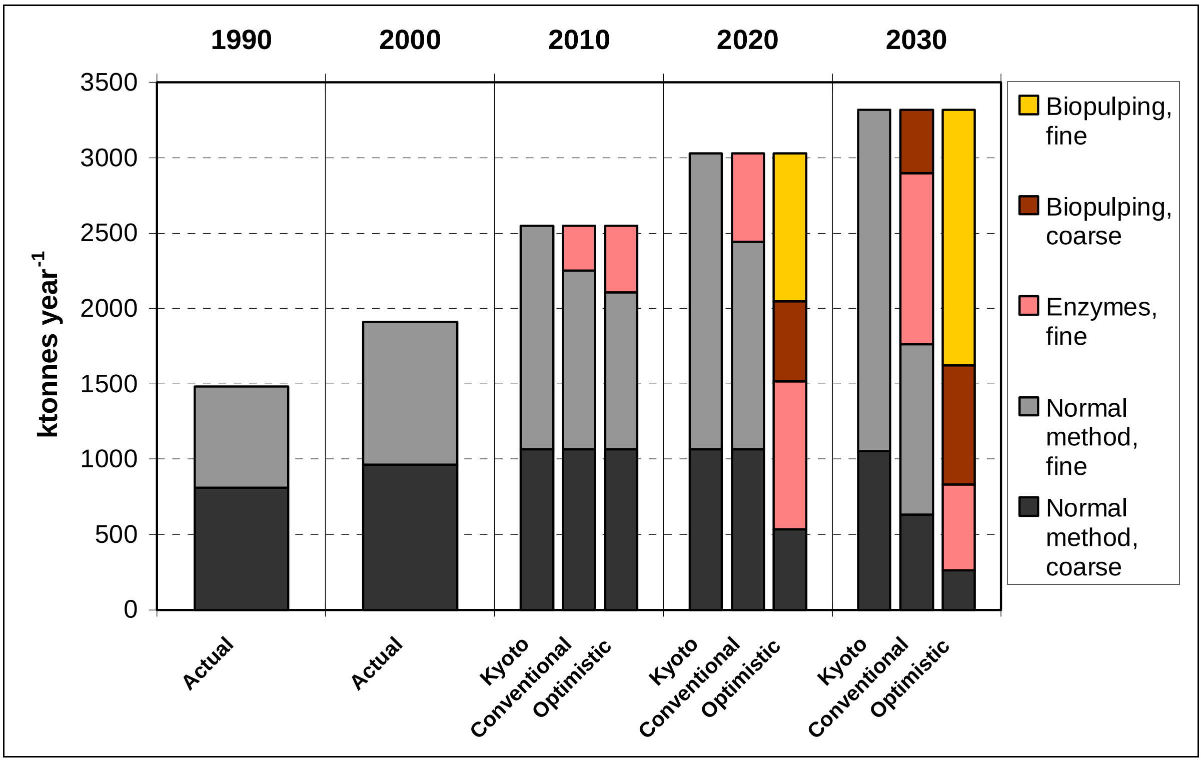

Figure 7. Penetration of biotechnical methods in mechanical pulping in the Conventional and Optimistic scenarios. In the Kyoto scenario the new methods were not considered.

The potential of new technology and its effects on the energy efficiency of appliances and lighting in households and offices were studied within one of the CLIMTECH projects. By using the best existing commercially available energy-efficient technologies, the expected decrease in electricity consumption would by 20% in household electronics, 65% in lighting, and 14% in refrigeration compared to the Baseline scenario. Of the technically possible savings, 2.1 TWh annually, about 1.2 TWh proved to be economically feasible in the optimistic scenario. Concerning offices, the study revealed a very large saving potentials in electricity use compared to the Baseline scenario. However, due to lack of up-to-date cost estimates, in the scenarios only a small part of that potential was realized.

Emissions from the transport sector are affected by transport volumes, demographic changes, modal shares of passenger and freight transport, driving styles and technology development. In the scenarios the assumptions concerning the development of transport volumes and modal shares were fixed projections. Consequently, the scenarios differ only in the development of technologies and market shares within transport modes. While in the conventional scenario new vehicle technologies were not assumed to become competitive on large scale, in the Optimistic scenario hybrid cars, and later fuel cell cars, were assumed to become leading technologies in the passenger car markets, as illustrated in Figure 8. However, the economic advantage of the new technologies was assumed to be only marginal, so that the actual costs would nevertheless increase slightly while savings in total consumer expenses would be are achieved through lower tax proceeds on transport fuels.

Methane emissions from waste management can be reduced in a number of ways. Disposal of waste to landfill sites can be reduced by preventing waste generation, by material recycling, composting and putrefaction, as well as by the use of waste for energy. Methane emissions generated at landfills could be mitigated by increasing the recovery of landfill gas and by the oxidation of methane to carbon dioxide. Reducing methane emissions by the utilization of either waste or landfill gas for energy can be particularly advantageous, because carbon dioxide emissions from fossil fuels would be reduced as well. According to the results from the scenarios, the use of recycled fuels is indeed one of the most cost-effective means to reduce greenhouse gas emissions in Finland. However, as most of the potential is economically attractive already in the Baseline scenario, the full contribution of waste management to GHG emission reduction is not visible in the results.

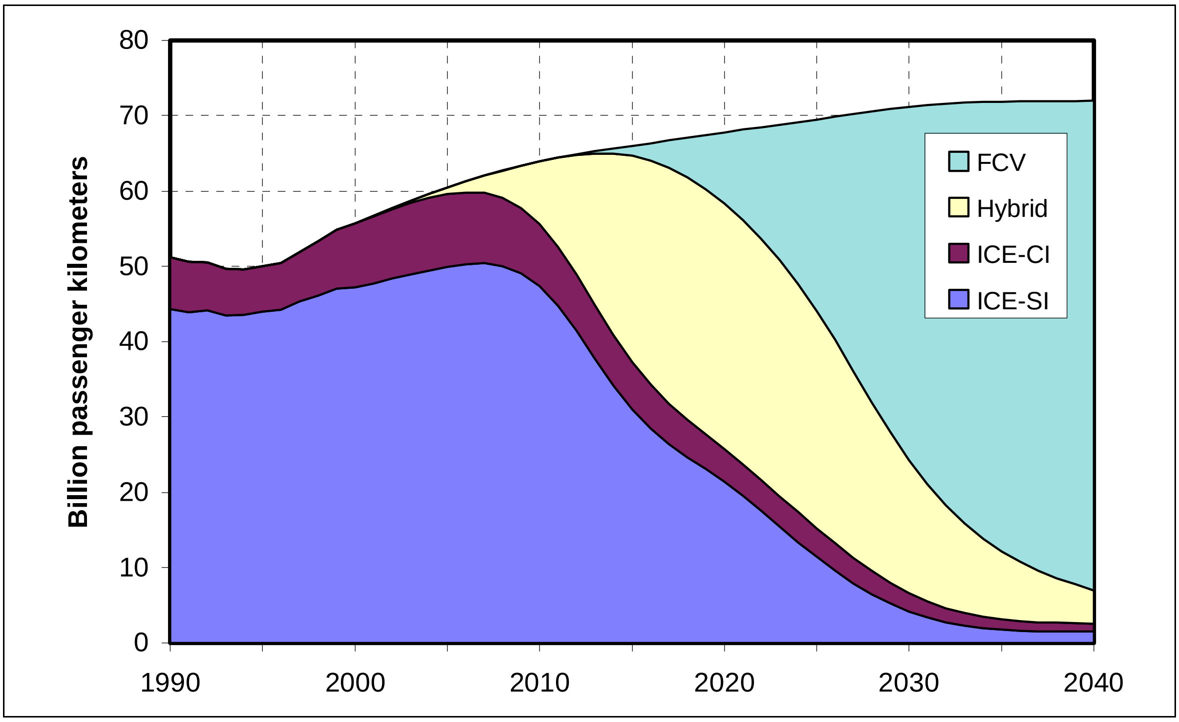

Figure 8. Penetration of new passenger car technologies in the Optimistic scenario.

The emissions of fluorinated gases (F-gases) known as HFCs, PFCs and SF6 are projected to increase rapidly in Finland, mainly due to the increasing use of HFCs as substitutes for ozone-depleting refrigerants, and because of the expanding use of commercial refrigeration and air-conditioning systems (Oinonen & Soimakallio 2002). According to the scenario results the emissions can be significantly and cost-effectively reduced by minimising gas leakages into the atmosphere, and, in the longer run, by alternative technologies and working fluids that can be developed and adopted in many uses of F-gases.

5.4 Greenhouse gas emissions

According to the results from the Baseline scenario, the total GHG emissions would increase about 17% from the 1990 level by 2010, and about 30% by the year 2030. The Baseline scenario corresponds roughly to the BAU scenario of the National Climate Strategy prepared in 2001 (Government 2001), and thus includes no increase in nuclear power, unlike the other scenarios. The new nuclear reactor assumed to be operational in 2009 decelerates the increase in emissions, but not nearly sufficiently with respect to the emission targets.

The development of greenhouse gas emissions is shown in Figure 9 in all scenarios with base targets for emission reduction. Until the year 2010 there are only small differences between scenarios. In conformity with global trends, emissions from energy production and transports have the strongest tendency to increase in Finland due to increasing electricity use and transportation volumes. Without new emission targets beyond Kyoto, the emissions from energy production would increase continuously until 2030. On the other hand, in the scenarios with the 20% reduction target most of the additional emission reduction measures would, indeed, take place in energy production, in particular in the Conventional scenario. However, reductions below the 1990 levels appear to be in general most cost-effective in methane emissions and in CO_2 emissions from small combustion.

The potential impacts of emission trading on the Finnish energy system were also analysed in both the Conventional and Optimistic scenario. The market price of emission allowances was assumed to

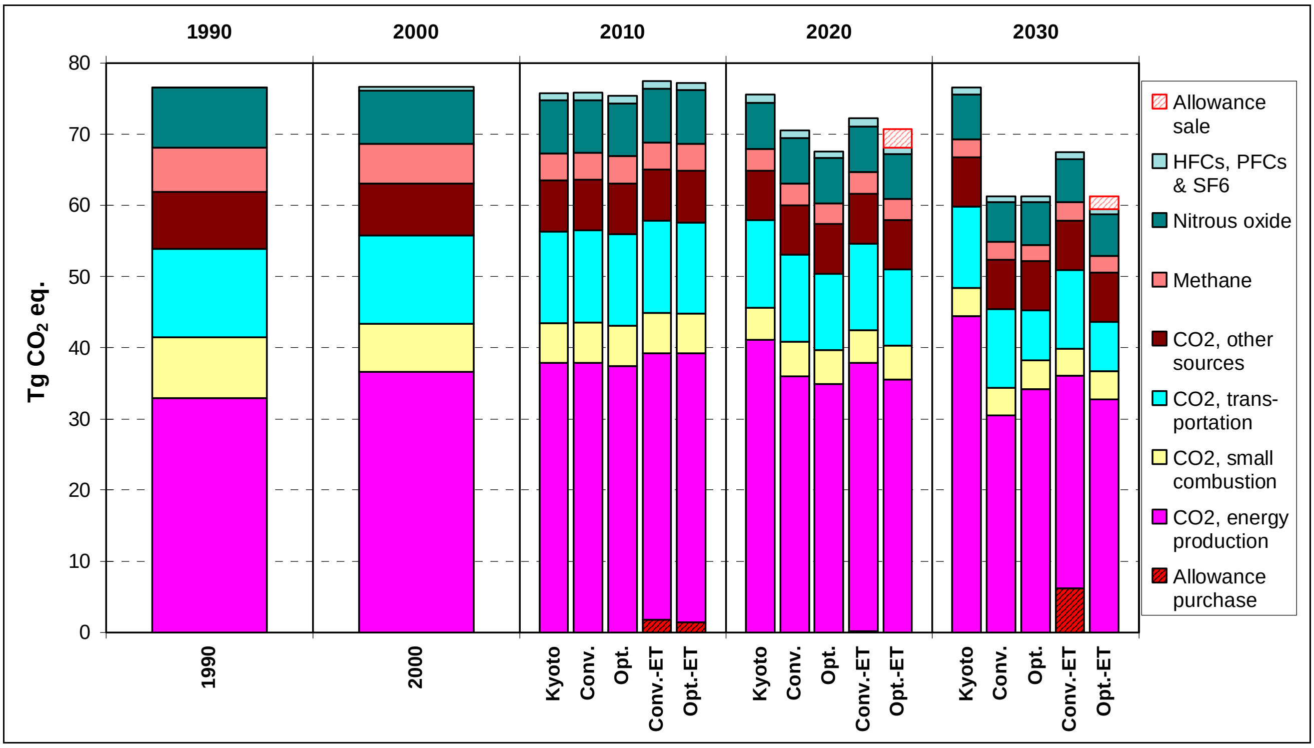

Figure 9. Greenhouse gas emissions by main category between 1990 and 2030 in the scenarios with base emission targets. Scenario variants including CO_2 emission trade are marked with the suffix 'ET'.

be 10 € / tCO_2 in 2010 and then increasing linearly to 30 € / tCO_2 in 2030. As illustrated in Figure 9, the differences between the scenarios are emphasised in 2030. In the conventional scenario it appears to be profitable to purchase relatively large amounts of emission allowances, whereas selling them proves to be profitable in the optimistic case. The rapid development of technologies creates notable opportunities for the sales of emission allowances instead of need for purchases. Under an emission trading system, investments in technology development can thus lead to substantial side-benefits in the from of positive net cash-flow from the emission allowance market and, at the same time, expanded market opportunities for the developers of new technologies.

While Figure 9 illustrated the cost-effective allocation of emissions by main source category, Figure 10 shows rough estimates of the allocation of cost-effective emission reductions by main technology groups in the optimistic scenario for the year 2030. The reduction curves have been estimated by varying the overall emission reduction target from about 5% to about 30%, corresponding to a marginal emission reduction cost between 5 € and 40 € per tonne CO_2 equivalents. One should bear in mind that, in general, the total emission reductions cannot be accurately allocated to single technologies, as the various substitutions occurring in the energy system between technologies and energy forms are often quite complex and ambiguous.

For comparison, also the calculated impact of nuclear power on total greenhouse gas emissions is shown in the figure, although the amount of new nuclear power capacity was assumed to be the same in all scenarios, except for the Baseline scenario. The results show clearly that, apart from the new nuclear power plant, biomass-based power and heat generation technologies as well as wind power systems are by far the most important technology groups in terms of cost-effective GHG emission reduction potential in Finland. Nevertheless, there is a wide variety of other technologies that should not be neglected, albeit having a relatively small cost-effective potential individually.

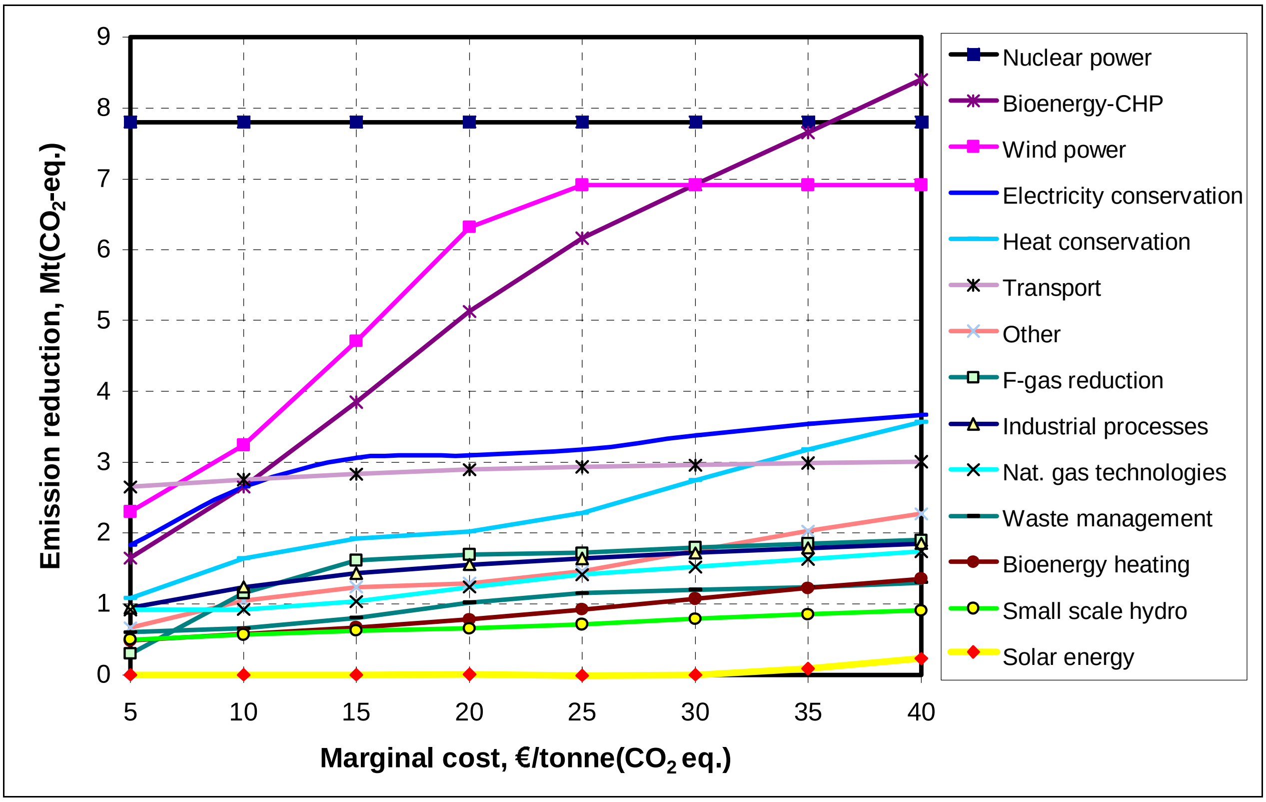

Figure 10. Emission reductions achieved by major technology groups as a function of marginal emission reduction costs in the optimistic scenario in the year 2030.

5.5 Other air emissions

The significant changes in energy production and consumption caused by the limitation of greenhouse gas emissions may induce substantial changes in emissions of other pollutants as well. Within the CLIMTECH scenario study, the side effects of climate change mitigation on other air pollutant emissions were investigated (Syri 2002). The EFOM model was expanded by adding modules for the calculation of fine particle emissions. In addition, the existing routines and databases for the calculation of sulphur and nitrogen oxides in the EFOM model were updated to correspond to the latest status of reduction technologies and recent amendments in emission control legislation (e.g. EU 2001a,b, European Commission 2000). The model was used to find the least-cost measures for achieving the specified greenhouse gas emission reductions, and the simultaneous changes occurring in the emissions of other air pollutants were calculated.

The structural changes in the energy and industrial system that are needed to achieve substantial GHG reductions were found to induce significant side benefits as reduced emissions of sulphur and nitrogen oxides. Table 3 summarises the results for the 20% GHG emission abatement scenarios. The results appear to be in line with earlier studies (e.g. Syri et al. 2002). A structural reduction of 11–16% in total sulphur emissions can be expected in comparison to the Kyoto scenario. The main mechanism causing structural reduction in sulphur emissions is the diminishing use of sulphur-containing fuels, mainly coal and peat.

Nitrogen oxides (NO_X) emissions are expected to decrease considerably in the future due to the penetration of new engine technologies in the vehicle fleet (Table 3). A further decrease of 8–9% from the Kyoto scenario would occur with a –20% GHG restriction. This is mainly due to the penetration of new technologies in the transport sector, such as hybrid engines and fuel cells, in the Optimistic scenario after the year 2020. In the Conventional scenario, the decrease in total NO_X emissions is caused by the smaller total energy use in the energy and industrial sectors. This decrease is partly offset by the remaining larger emissions with the conventional technologies in the transport sector.

The study indicated that structural GHG reduction measures do not warrant simultaneous particulate emission reductions. This is caused by the fact that large-scale combustion plants utilising fossil fuels are equipped with very efficient particulate emission controls in Finland, and a shift towards smaller-scale combustion of biomass may actually increase particulate emissions unless advanced control technologies are employed.

Table 3. Air pollutant emissions in Finland in 2000 and in 2030 according to the Conventional and Optimistic scenarios with a –20% greenhouse gas reduction requirement. The situation in 2030 with GHG emission stabilization at 1990 level (Kyoto) is shown for comparison.

	2000	**2030**		
Emissions	**Actual**	**Kyoto**	**Conventional**	**Optimistic**
Sulphur (Gg SO_2)	85	81	68	71
Nitrogen oxides (Gg NO_2)	208	128	114	116
Particulates (Gg)	49	30	29	30

5.6 Overall economic implications

The aggregate economic results of the energy system model include total investment, fixed and variable operation costs by sector, prices of imported fuels and electricity, as well as taxes and subsidies. As no emission targets were assumed in the Baseline scenario, the total direct costs of emission reduction can be calculated as the difference in the total costs in each reduction scenario compared to the Baseline scenario, excluding any taxes and subsidies. Figure 11 illustrates the differences in the emission reduction costs between the various scenarios on an annualized basis. Investments costs of technologies have been annualized by using a capital recovery factor based on the assumed economic lifetime.

The results of the scenario study indicate clearly that a boosted development of new technologies can have a significant impact on the direct emission reduction costs. The tighter the emission abatement goals are, the wider becomes the cost difference between the Conventional and Optimistic scenarios. With the 20% reduction target the difference in costs is almost 500 M€ per annum in 2030, and with the 30% target the difference is increased to about 800 M€. It also appears to be evident that the earlier clean technology becomes competitive and gets implemented, the greater will be the gradually realized cumulative cost savings.

The total annualized cost impacts of emission trading can also be seen from Figure 11. As mentioned earlier, the market price of emission allowances was assumed to increase linearly from 10 € / tCO_2 in 2010 to 30 € / tCO_2 in 2030. While the Conventional scenario represents a net buyer of emission allowances throughout the period, the Optimistic scenario becomes a net seller of allowances between 2010 and 2020, and remains its positive trade balance thereafter. The net impact of emission trading on the total costs remains quite small in the scenarios. However, one should note that the price of emission allowances was assumed to be directly reflected in the price of imported electricity, which leads to an increase in the total costs in the trading scenarios.

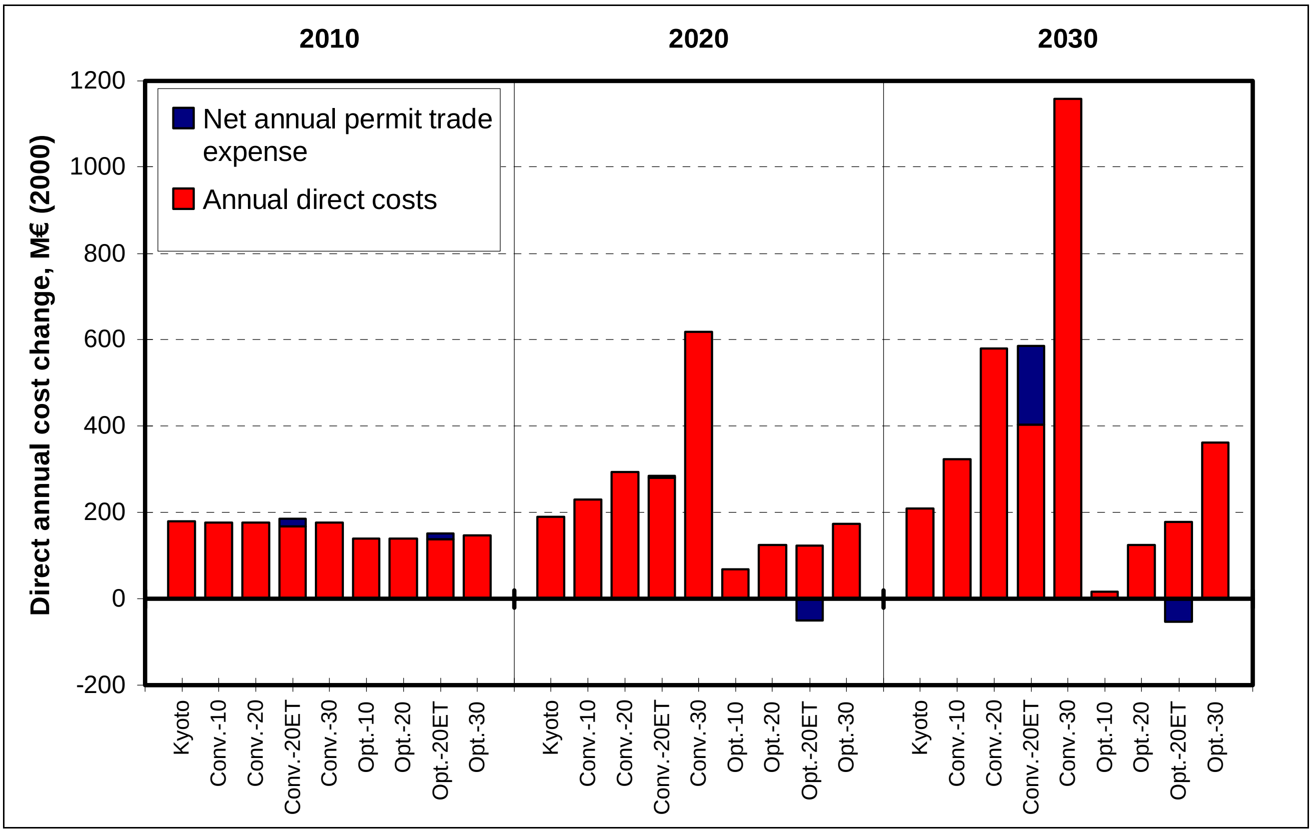

Figure 11. Direct annual emission reduction costs in the scenarios considered.

6. Conclusions

The objective of the study was to assess the role of technology development in the greenhouse gas emission control in Finland mainly on the basis of studies made in the CLIMTECH technology programme. The task was carried out using an energy systems model, which has been extended to describe practically all emission source categories and all gases of the Kyoto protocol with a relatively detailed technology level. The systems model approach can be used to give commensurate results concerning the potentials and costs of technologies.

Two alternative scenarios that describe different development rates of technologies were used in the study. In the first one the pace of technology development was assumed to be conventional, but in the second faster or boosted development was assumed, which implicitly implies greater investments to the technology development leading to faster improvements in economy and efficiencies.

The scenarios also included considerations about the projected impact of climate change on energy production and the consumption of space heat. While these estimates were based on a relatively detailed study made under the CLIMTECH programme, they were still quite preliminary and contain large uncertainties. Further studies with more detailed climate projections from regional scale models would be necessary for more reliable estimates.

Climate change itself may boost the deployment of advanced wind power technology by the improved economics due to the estimated growth in average wind speeds. As earlier studies have indicated beneficial impacts also on biomass production, similar boosting effect may occur for advanced biomass energy production technologies as well. Since bioenergy has a very significant role in the Finnish energy system, further studies would be important for the estimation of the plausible future changes.

According to the results of the study, strong investments in the development of technology would have a great impact on the energy production and consumption system and on the emissions of greenhouse gases in the next 20–30 years. The direct costs of emission control would typically be roughly lowered by a factor of three in the case of optimistic technology development compared to conventional development. In absolute terms this is nearly 500 million Euros annually around 2030 in the case of 20 per cent emission reduction. This can be compared with the present public R&D expenditure in energy technology, which is about 50 million Euros per year (see Figure 1). However, due to the slow changes in the energy system, the potential of technology can only be realized in full if the investments in technology development are made in time.

In addition to the decrease in the direct costs of greenhouse gas emission control, there are many other benefits from intensive investments in the development of technologies that reduce greenhouse gas emissions. By staying at the cutting edge of technology know-how the opportunities for technology exports will be substantial. Presently the export of energy technology equipment from Finland is already large and it is increasing strongly. The demand of new and more efficient energy technologies can be expected to increase in the global markets. The technology markets of wind power are still increasing by tens of percents yearly. Currently, the Finnish industry manufacturing wind power components has considerable share of the global markets and, hence, even if the market share would not increase the export of technology is likely to grow.

The Finnish market share of advanced boilers that can be used to combust heterogeneous fuels efficiently is also already large. The growing demand of bioenergy technology might also clearly benefit the Finnish industry. In addition to bioenergy and wind energy, many other renewable or efficient energy technologies have a similar situation.

Investing in new technology reduces the emissions of greenhouse gases and also reduces the costs of emission control, which can enable selling of greenhouse gas emission allowances instead of purchasing them. This can be seen as a beneficial source of income both at the company level and at the level of the national economy. On the other hand, slow deployment of technology will much more likely imply a considerable need for the imports of emission allowances. The results thus indicate a clear relationship between technology development and national emission trade balance.

The reduction of greenhouse gas emissions reduces also the emissions of many other air pollutants or makes the control of other emissions less expensive. This is valid also in Finland, but it is much clearer in many developing countries where relatively little effort is put to control emissions of other pollutants. Reduction of greenhouse gas emissions reduces SO_2 and NO_X emissions. Concerning particulate emissions, there is a risk that increasing the use of simple biomass combustion techniques increases particulate emissions. Therefore, attention should be paid on the control of particulate emissions e.g. by using advanced combustion or gasification techniques that also have higher efficiencies and thus lower fuel consumption.

Sorted out of the numerous technologies considered in this scenario study, nuclear power has, as a single technology, the largest direct impact on emissions reduction. Bioenergy has a very important role in Finland already at present, and its role will become even more prominent in the future. The technologies and uses of bioenergy are quite diverse. Bioenergy is used in both industry and communities, to a large extent in combined heat and power production. The share of electricity produced with biofuels will grow in the future due to both higher power-to-heat ratios and more distributed CHP generation. New fuels based on biomass, such as pellets and pyrolysis oil, enter the markets, and the gasification of solid biomass and waste fuels has great potential. Biomass based components will also be added to transport fuels.

The production of wind energy can also be expected to grow rapidly during the next 30 years from its present very small share in Finland. In the optimistic technology development scenario its share would even well exceed ten percent in 2030. Many other technologies in the energy production side are also quite cost-effective. Examples of these are small-scale hydropower plants and high-efficiency CHP technologies based on natural gas. However, as natural gas is a fossil fuel, in the case of deep emission reductions its extensive use is no longer very advantageous.

Efficiency improvements in the use of electricity and heat are of vital importance. There are many technologies contributing to this both in industries and in the residential and service sectors. A good example of such technologies in the industrial sector is the biotechnical treatment of wood chips in energy-intensive mechanical pulping. Examples in the household sector are e.g. efficiency improvements through changes in lighting, refrigeration and household electronics.

Reductions of non-CO_2 greenhouse gas emissions contribute also to the cost-effective control strategies. Limitation of N_2O emissions from nitric acid production as well as the reduction of CH_4 emissions from waste management appears to be very cost-effective. Methane emissions can be recovered from landfill sites and destroyed by flaring, or in case of larger landfills, used for energy production. Also the amount of waste to be landfilled can be controlled by increasing recycling or by using the waste as fuels. The rapidly increasing emissions of the fluorinated Kyoto gases can be in many cases cost-effectively controlled by improving the integrity of the equipment and by using other technological solutions such as less harmful refrigerants.

In summary, systematic investments in technology development will lower the costs of greenhouse gas emission reduction considerably at company and national level. The investments in technology development will also produce many other benefits than reduced costs of emission control. They will create income through technology export and possibly also through sales of emission allowances. They will also make the control of many other air pollutants easier.

Moreover, the decrease in the costs of greenhouse gas emission abatement through technology development can also have multiplicative benefits with respect to climate change mitigation. Lower costs will enable deeper emission reductions in the long term. This is in practice a necessary condition for the stabilisation of the concentration of the greenhouse gases in the atmosphere, which is the ultimate objective of the Climate Convention.

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