Renewable Energy Sources and Distributed Energy Production

Wind Power in Finland – Export Prospects and Emission Reductions

Tuulivoima Suomessa – vientipotentiaalia ja päästövähennyksiä

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Abstract

Wind power, as a renewable source of energy, reduces the greenhouse gas emissions. For Finland, the technology also brings business opportunities, as the Finnish industry already has a position in the global, fast growing wind power market. The wind energy project within the Climtech Programme focused on the technology export potential of Finnish industry in wind power markets, and on the reduction of greenhouse gas emissions of wind power in the Finnish and Nordic energy systems.

The global development of wind power technology and market prospects of wind power were taken for a starting point when estimating the technology export prospects for the Finnish industry. If the Finnish industry is able to maintain the current market shares, the exports will be 0.8–1.2 billion € in 2010. If the Finnish wind turbine manufacturer were able to get a global market share of 5%, this would more than double the Finnish exports. The fast growing wind power market is abroad. To stay there, or to get there as a newcomer, requires more and more national support in the form of R&D and a home market.

For the emission reductions, simulations for the Finnish and Nordic energy systems were conducted to find out the amount of emission reductions wind power could make. CO_2 emissions will be reduced 700–650 gCO_2/kWh wind produced. The costs for CO_2 abatement by increasing wind power capacity in Finland seem to be about 20 €/t CO_2 for the first TWh of wind, and when the capacity is further increased the costs also raise gradually to 35 €/t CO_2 for the seventh TWh of wind.

Lyhennelmä

Tuulivoima on uusiutuva energiantuotantomuoto, joka vähentää kasvihuonekaasupäästöjä. Suomelle tuulivoimateknologia tuo myös liiketoimintamahdollisuuksia, koska suomalaisella teollisuudella on jo vahva jalansija voimakkaasti kasvavilla maailmanmarkkinoilla. Climtech-ohjelman tuulivoimaprojektissa tarkasteltiin Suomen teknologiaviennin mahdollisuuksia tuulivoimamarkkinoilla sekä tuulivoiman päästövähennysmahdollisuuksia Suomen ja Pohjoismaiden energiajärjestelmässä.

Arvioitaessa tuulivoimateknologian vientipotentiaalia lähtökohdaksi otettiin markkina-arviot sekä tuulivoimateknologian kehitystrendit maailmalla. Mikäli suomalainen teollisuus pitää nykyiset markkinaosuutensa kasvavilla markkinoilla, teknologiavienti vuonna 2010 on 0,8–1,2 mrd €. Mikäli suomalainen tuulivoimavalmistaja saa 5 % markkinaosuuden, teknologiaviennin arvo yli kaksinkertaistuisi tästä. Kasvavat ja voimakkaasti kehittyvät tuulivoimamarkkinat ovat ulkomailla, ja siellä pysyminen tai sinne pääseminen vaatii enenevässä määrin kansallista tukea: t&k-toimintaa sekä kotimarkkinat.

Tuulivoiman päästövähennyksiä arvioitaessa simuloitiin Suomen ja Pohjoismaiden energiajärjes-

telmiä. CO_2-päästöt vähenevät 700–650 gCO_2/kWh tuotettua tuulivoimaa kohti. CO_2-päästösäästöjen kustannukset ovat simulointien mukaan noin 20 €/t CO_2 ensimmäiselle TWh:lle tuulivoimaa, ja kun tuulivoimaa lisätään suuria määriä, kustannukset kasvavat asteittain tasolle 35 €/t CO_2 seitsemännelle TWh:lle tuulivoimaa.

1 Introduction

Wind power, as a renewable source of energy, reduces the greenhouse gas emissions. For Finland, the technology also brings business opportunities, as the Finnish industry already has a position in the global, fast growing wind power market.

The wind energy project within the Climtech Programme focused on the technology export potential of Finnish industry in wind power markets, and on the reduction of greenhouse gas emissions of wind power in the Finnish and Nordic energy systems.

With global development of wind power technology and market prospects of wind power as a starting point, the technology export prospects for the Finnish industry were estimated. Also the national activities, including R&D, required to achieve the export potential were estimated.

For the emission reductions, simulations for the Finnish and Nordic energy systems were conducted to find out the amount of emission reductions large-scale wind power could make in the system.

2 Wind power market opportunities for Finnish industry

2.1 Wind power technology trends

The most important wind power trends in near future are increasing unit size, increasing project (wind farm) size and the start of large-scale offshore installations. For turbine technology, the trends are increased use of control and smart structures, increase in gearless or partly direct drive concepts, and shift towards variable rotating speed. Larger production units require new solutions for regulation of the production and the network.

The wind turbine unit size has increased 10-fold in 10 years. The nominal power of the wind turbines is presently between 0.6 and 2.5 MW. The next step will be from the 2 MW turbines to 3–5 MW units (Fig. 1). The turbines can be installed on land at least up to 2–3 MW. On estimate, 5 MW turbines will be commercialised around the year 2005, and turbines up to 10 MW have been considered technically feasible. The large turbines will be designed for offshore sites.

The basic concept – a two or three-bladed turbine with a horizontal axis – seems to remain in the future. In the megawatt turbines the stall control seems to give away for pitch or active stall control. As the unit size increases, load monitoring, control and smart structures become more important. Offshore wind farms will set new requirements for the design and implementation for wind power plants. Especially the requirements for reliability and lifetime will increase. In the future there will be special offshore and on-shore wind turbines, instead of turbines with offshore modifications in the market today.

In spite of the development of gearless solutions, the market share of turbines with gears will stay large, and also increase in the future. Large turbines will have their market predominantly offshore. Offshore markets have been estimated to remain at a level of about 10% of the global wind power markets.

Looking at the global wind technology trends from the Finnish industry point of view, the components for the turbines will contain more special know-how. Especially offshore installations increase the need for condition monitoring and preventive maintenance. The concept solutions of the turbine manufacturers have to be taken into account from the beginning during the development, design and optimisation of the components. This will lead to different products for different manufacturers, which will bring about increased development costs and need for pilot plants. Increasing project size will also increase risks involved in new technical solutions, especially when taken into use for the first time far from Finland.

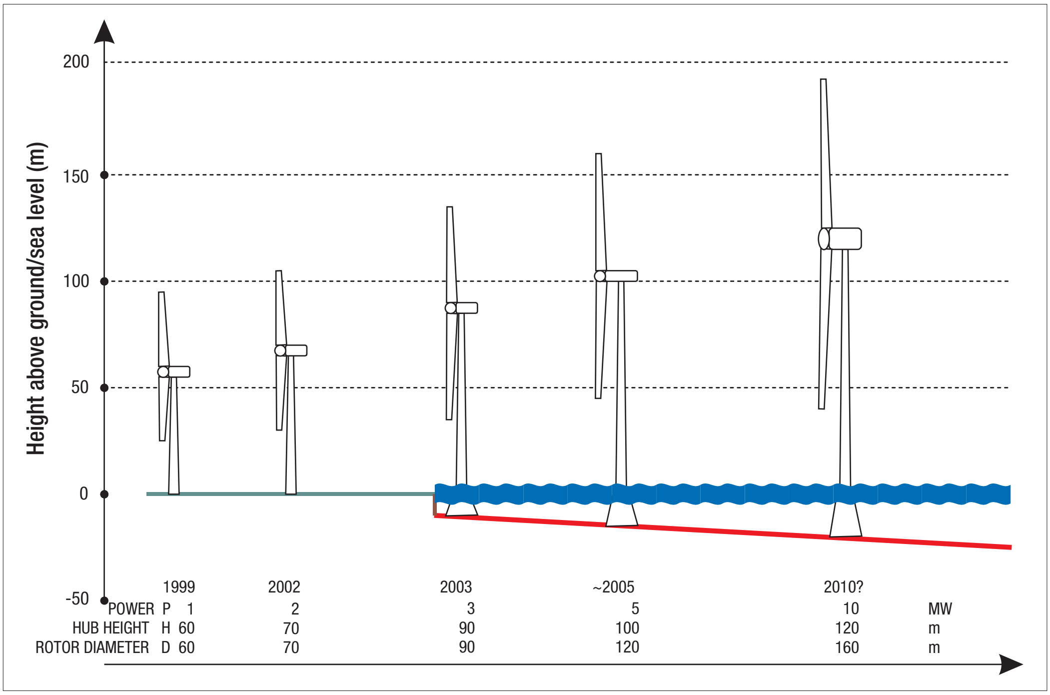

Figure 1. Expected increase in the unit size of wind power plants in the future.

2.2 Finnish industry has a strong position

The Finnish industry manufactures 10 to 20 per cent of the main power plant components. Wind technology exports amounted to over 170 million € in 2001, which accounts for five per cent of the total wind power market. In 2001, the first 1 MW pilot plant of the Finnish wind turbine manufacturer, WinWinD, was installed. International project development has been initialised in 2001.

ABB Finland Oy, a corporate responsible for small generators within the international consolidated corporation ABB, is the market leader of wind turbine generators with a market share of 20–30%. The market share has been growing especially in the megawatt class turbines. Also frequency converters are manufactured in Helsinki.

The Finnish Metso group has several wind power business areas. Metso Drives (former Santasalo and Valmet) manufactures gears, with a 10–15% market share. Metso Valimo has recently been increasingly manufacturing large castings, like nacelle and hubs. Metso Automation offers condition monitoring and together with Metso Drives they have developed a smart gear concept.

Ahlström Oy Fiberglass has been active in wind power business since early 1980's. It manufactures glass-fibre products to suit the blade manufacturers' needs. Exel Oy is producing pre-fabricated fibre-enforcements for the blade manufacturers.

During the last few years there has been increasing export of materials for towers, like pre-manufactured steel plates and flanges for towers (Rautaruukki and subcontractors). The first ice prevention systems for wind turbine blades including special ice detectors of Labko Oy were exported in 1998 by Kemijoki Arctic Technology. Vaisala Oyj is a strong company with wind and other meteorological sensors already in use in wind speed measurement campaigns, but has opportunities for export of control anemometers for wind turbines.

Further subcontracting opportunities for the metal and machinery industry include e.g. manufacturing of towers directly to turbine manufacturer, for the market area Finland and Baltic sea area, yaw gears directly to turbine manufacturer and cog-wheels as a subcontractor to gear manufacturers.

Products in reinforced plastics also have opportunities to grow in Finland. Manufacture of blades on licence for the arctic applications offers a special opportunity in Finland. So far a manufacture of ice prevention systems directly integrated to blade manufacturing process does not exist. The importance of pre-manufactured girders and other pre-fabricated products for blades may grow with the growing size of blades.

2.3 Growing wind power markets globally

Wind power is growing fast globally, especially in Europe. At the end of the year 2001, the wind power capacity of the world was 24 000 megawatts (MW), of which major part, more than 17 000 MW in Europe. In 2001 the new installed capacity was about 6 000 MW, corresponding to a market value of roughly 6 billion €. The growth rate has been 25–40% in recent years. Strong growth is expected to continue for several years.

The estimations in this study are based on the wind power market update of BTM Consult (BTM Consult 2001). This annual market analysis has been published since the 90's. The total cumulative capacity of wind power is estimated to be nearly 60 000 MW in 2005 (40 000 MW in Europe) and 140 000 MW in 2010 (80 000 MW in Europe). The annual demand for wind power is estimated to be 10 000 MW a year in 2005 and 25 000 MW a year in 2010. According to these forecasts, the high growth will continue until 2005, after which the growth in Europe will level out, but will continue high in other parts of the world, Fig. 2.

2.4 Good export prospects for Finnish wind technology

The development of Finnish wind technology export in the future depends on the ability of the component industry to maintain, or even increase the market shares of the fast growing wind power mar-

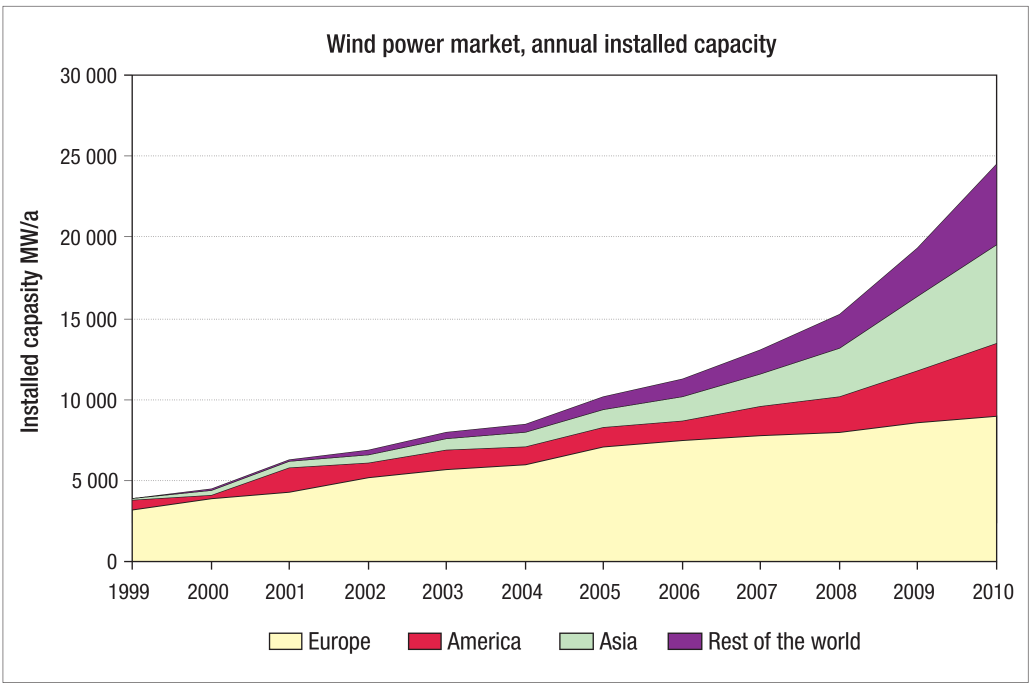

Figure 2. Annual installed wind power capacity, estimated development until year 2010.

ket. The new Finnish turbine manufacturer's ability to get a hold of the global market also impacts the potential by strengthening the already existing technology cluster. The networked co-operation provides opportunities for more exports related to blade technology, tower structures, control systems and the setting up of offshore wind farms.

The export of Finnish wind power technology for year 2010 has been estimated based on the global wind power market forecasts and the development of Finnish market share in the markets. The base case has been taken directly from the forecasts of BTM Consult, a 25 000 MW/year global market in 2010. A more conservative estimation of 15 000 MW/year has been included corresponding a 10% average growth rate in 2002–2010. The cumulative installed wind power capacities in 2010 according to these market projections are 140 and 120 GW, respectively.

The value of the market has been estimated taking an average cost of total investment of wind power as 1 million €/MW. Here the turbine accounts for 0.7 million €/MW. In reality the unit cost of investments depends on the site. It is higher for offshore wind farms and arctic applications. Offshore market is expected to account for 10% of the total market in 2010. The value of the total market is estimated as roughly 25 and 15 billion € in 2010, for the two market projections.

The export prospects are presented in Fig. 3, for two global market projections and for three strategies. In a "business-as-usual" strategy, no new products or concepts are sought for and the goal is to keep the present market share in the present products. Under these circumstances the exports in year 2010 would be 1.2 billion €. The next strategy is to actively develop current products, aiming at a 50% increase of market share. This would mean for example smart gears and generators improving the reliability and decreasing the maintenance costs. Succeeding in these concepts, as well as manufacture of blades in Finland, requires more profound know-how of wind power technology than today and close collaboration with turbine manufacturers.

In the third projection, Finnish wind turbine manufacturer succeeds in reaching a considerable market share in the global markets. In this case the export prospects would be in the range of 2–4.5 billion € in 2010, depending on the market share. The

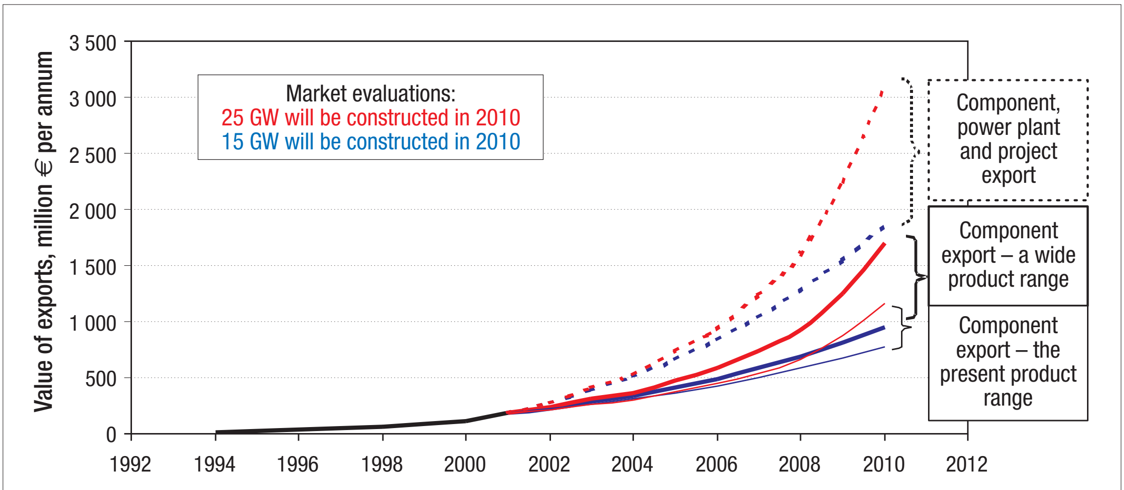

Figure 3. The export prospects of wind power technology until the year 2010 based on two different evaluations of the world market. There are three strategies to compare: the present product range, a substantial investment in technology development (a wide product range) and an investment also in the domestic market (export of also wind turbines and projects).

cumulative exports in 2002–2010 would exceed 8–14 billion € with the same assumptions made.

If the global market develops according to the lower projection, the export prospects are 0.8 billion € with current component market shares and 1.3–2.6 billion € with Finnish wind turbine manufacturer having a market share between 2–10%.

For comparison, the total technology exports of the Finnish energy sector was 4 billion € in 1998. For Finnish wind power, it is obvious that technology export prospects is a more important technology driver than the renewable energy production from wind power.

2.5 Needs for R&D to improve technology exports

In the interviews of Finnish industry, it became clear that maintaining the market share in the global wind power market is challenging. The suppliers capable of increasing the production as fast as the market have a strong position. Development and tailored products are a prerequisite, and both a home market and investment in R&D are important and needed. Large, already established actors can maintain their exports also in the future without a home market, but as long as turbines and components are under heavy development work, demonstrating new solutions nearby enables also the component manufacturers to have important first references.

Goals for the national wind technology R&D can be divided into 5 topics. *Wind turbine concept based on semi direct drive*, low speed machine, to achieve an exceeded lifetime of at least 30 years, has a target of significant market share globally at least in drive train components. *Blade technology* to fit cold and icing conditions, both in mountainous areas and by the sea, would enable increased rotor diameter with modular solutions. *Foundation and installation techniques for Baltic sea offshore* wind farms to apply for different sea bottom conditions and water depths, has to manage combined wind, wave and ice loads on foundations and tower. *Wind turbine control and network connection* concept aims to improve the management and control of large wind farms especially regarding to power production and network stability. *Development of smart components* aims to increase lifetime and decrease fault sensitivity and O&M costs.

Besides the technology R&D, there are several aspects of R&D relevant for wind power production and operation in Finland. Even though the standard, Central European technology can be directly applied in Finland, there are some special features calling for national R&D. *Better knowledge of the wind resource:* long term measurements offshore and at altitudes relevant for wind power, 50–150 m above ground or sea level, including ice conditions. Wind atlas needs updating and adjusting to the forested coastal and arctic fell terrains. *Wind power integration to the electricity system*: need for more flexibility to accommodate the varying wind power production will become topical when more than 5% of Finnish electricity is produced with wind. Short term prediction of wind power production will be needed by the system operator, and also producers, to help scheduling and market trade. *Follow up of production, failures and costs of wind power in Finland (statistics):* operational experience of wind power in Finnish climate and terrain is of value to producers, while the turbine types and concepts are new. Estimates for the production reliability and O&M costs are needed when making decisions for investments.

A road map for research, technology development, demonstration and commercialisation of wind technology was sketched in order to exploit the export prospects described before and to fulfil the wind energy production targets set in the national climate programme. The following items were taken as the goal state

- Finnish wind turbine manufacture gains a global market share of 10% in 2010, with all main components manufactured by Finnish subcontractors or suppliers.
- The component suppliers in the market today maintain their global market shares in the growing markets.
- The Finnish cold climate blade technology dominates the market segment.
- Finnish consortium achieves 10% market share of offshore wind farm projects in Northern Europe.

- The installed wind power capacity in Finland 500 MW in 2010, whereof 50% on the coast, 30% at sea and 20% on arctic fells.
- The Finnish wind power technology exports at an annual level of at least 2 billion € in 2010.

The summary of the road map in Fig. 6 gives the cumulative sum of investments from 2002 until 2010. The employment has been estimated from the export figures using an average value of 1 man-year per 100 000 € value of exports.

There are presently two research programmes in preparation and due to be launched in 2002 at National Technology Agency Tekes that include topics related to wind power technology: MASINA, technology programme for machines and, DENSY, programme for distributed energy. By means of a separate wind power research co-ordination, the R&D needs of wind power technology could be fulfilled using these R&D programmes. However, the studies and research relating to wind power production and operation would still be excluded from a research programme support.

3 CO_2 abatement of wind power for Finland

The electricity supplied by wind power is free from CO_2. When wind energy is replacing production forms that emit CO_2, the CO_2 emissions from the electricity system are lowered. The amount of CO_2 that will be abated depends on what production type and fuel is replaced at each hour that wind power is produced. This will be the production form in use at each hour that has the highest marginal costs. Usually this is the older coal fired plants, resulting in CO_2 abatement of wind energy of about 800–900 gCO_2/kWh, often cited as the CO_2 abatement of wind energy (EWEA 1996). This is true also for larger amounts of wind, for countries that have their electricity production mostly from coal.

For other countries, the situation may change when adding large amounts of wind power to the system. There might not exist old coal plant capacity for the whole wind power production to be replaced at all times of the year. Some hours of the year wind would be replacing other production forms, like

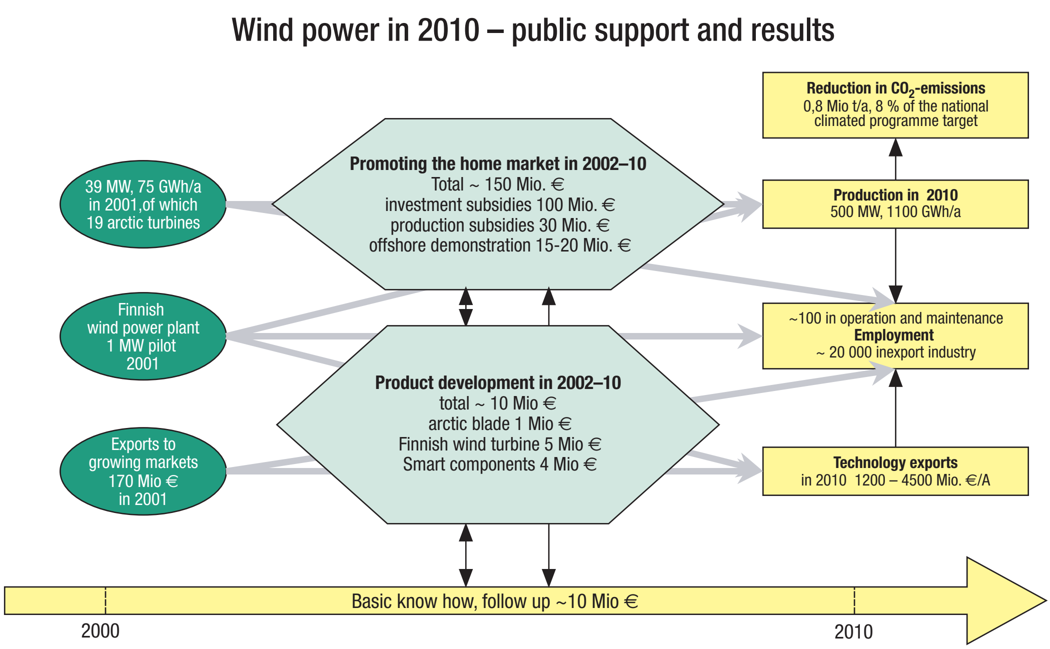

Figure 4. Wind power in Finland: opportunities and benefits achievable to year 2010.

gas fired plants production (CO_2 emissions of gas are 400–600 gCO_2/kWh), or even CO_2 free production forms, like hydro, biomass or nuclear power. To find out what will happen, the system has to be simulated. In the Nordic countries, the electricity system is characterised by a large share of hydro power. The deregulated electricity market in the countries has led to the joint electricity market Nordpool. It is therefore relevant to look at the whole Nordic system for CO_2 emissions with and without wind power.

The effect of wind power production on CO_2 abatement is simulated in two ways. By running simulations on the EFI's Multi-Area Power Market Simulator (EMPS) model for the whole of the Nordic electricity market we get the effects of wind power for an average, wet and dry year for the whole system. These simulations are based on electricity market operation with a fixed power production capacity, which takes into account the operating costs of each power production form only. By running EFOM for the Finnish energy system we get the effects of wind power to one country, also taking into account the investment to new capacity during a longer time period.

The simulations are made assuming that all the large-scale wind production will be available in the system. This means that local grid connection issues as well as the hourly variations of wind would be taken care of.

3.1 Simulations with EMPS model for the Nordic area

The power market model EMPS is a commercial model developed at SINTEF Energy Research in Norway for hydro scheduling and market price forecasting (Flatabö et al. 1998, Sintef 2001). EMPS simulates the whole of the Nordic market area, divided into areas with transmission capacities between the areas. The simulation is here made for one year, with weekly time steps. The model simulates a system where the firm consumption pattern and production system are static.

Two systems have been selected for the base case: electricity system for year 2000 and a suggested system for 2010 (MTI 2000, MTI 2001, Energy 21 1996). Wind is added to these base case systems step by step, cases wind1–wind3, to study the incremental effects of wind power on the system. We start with 16 TWh/a (wind1) and reach 46 TWh/a (wind3) annual total production in the Nordic countries. This corresponds to 4–12% of total electricity consumption and it is divided between the countries as 20–45% of consumption in Denmark and 2–10% of consumption in Sweden, Norway and Finland. Wind1 corresponds to existing targets for 2010 and wind3 is near possible targets for 2030.

To determine the market price and capacity needed for each week, we need the demand and a price for each production capacity. Operating costs given as input values are used for thermal production, taking into account the technical availability when composing the production/price curve for each time step. Water values are the prices used for hydro plants with reservoirs. These water values, the value of stored water at each time of the year, are calculated in the model by stochastic dynamic programming. If transmission capacity is restricted, there will be different prices in different areas, so basically the model simulates how the Nordpool market operates. Wind comes to the market as a price taker, with 0 bidding price, like the run-of-river hydro plants. The model takes into account the different inflow and varying wind situations by using historical inflow and wind data from 30 years as input for the simulation.

The simulation results for Finland show that wind production replaces condense production (mainly coal). Import to Finland increases. For wet years in the wind3 case (7 TWh in Finland and 46 TWh in Scandinavia) the nuclear production is slightly reduced (0.2 TWh). In Sweden, the electricity consumption in electric boilers is increased with increased wind production. This means that wind production is replacing oil (alternative fuel for the boilers). Wind production is replacing condense production, for the little there is to replace, and some of the nuclear and CHP production. Export of electricity is increased substantially. In Norway the consumption in electric boilers increases with added wind production. Export is also increased. In Denmark wind is replacing condense (mainly coal) and increasing exports. Both imports and exports in Denmark are increasing with increasing wind in the system. As wind production is added as extra production to the electricity system, about 40% of the wind production is transferred out of the Nordic countries with the transmission lines to Germany, Poland and the Netherlands (in the scenario for today's system about 30%).

Using emission coefficients for produced electricity from different production forms we can estimate the yearly CO_2 emissions of the simulated cases (fig.4). Coal, oil and gas fired units emit approximately 800, 650 and 430 gCO_2/kWh respectively. For combined heat and power production, the emissions for electricity are estimated to be about half of condense production, to account part of the emissions for the heat production. Biomass, nuclear, hydro and wind production are taken as CO_2 free production forms. The effect of electricity replacing oil used in boilers (price flexible consumption) is to lower the emissions, this is also taken into account in the emissions shown in Fig.5.

As a combined result of wind power replacing different fuel in the Nordic system, a CO_2 reduction of 700 gCO_2/kWh, adding the amount of wind foreseen in 2010 (wind1 simulation) is achieved. Adding more wind results in somewhat lowered emission reductions: 650 gCO_2/kWh in wind3 case. For the 2000 scenario the CO_2 reduction is slightly smaller, 680–620 gCO_2/kWh.

It is notable that the wind production added to Norway and Sweden will mostly replace thermal power produced in Finland, Denmark and Central Europe. This is a result of having an interconnected system with a common electricity market: power will be replaced where it is most cost effective. The hydro power in Norway and Sweden will not be replaced even with substantial wind production, as long as there are possibilities to increase the exports to other countries.

3.2 Simulations of the EFOM model for Finland

The EFOM model is a quasi-dynamic many-period linear optimisation model. It has been widely used to analyse national energy systems and mitigation of greenhouse gas emissions (e.g. Lueth 1997, Lehtilä and Pirilä 1996). In EFOM the network of the described energy system starts from the primary energy supply and ends in the consumption sectors. EFOM is a bottom-up model and it is driven by an exogenous demand in the consumption sectors. In addition EFOM includes descriptions of other activities that emit greenhouse gases (e.g. waste management and agriculture). The sys-

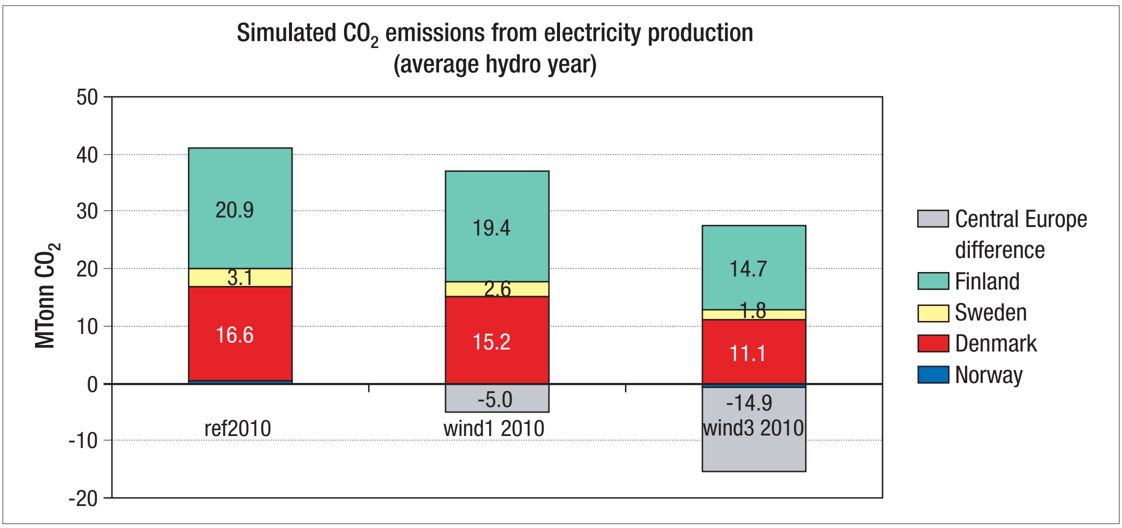

Figure 5. CO_2 emissions in reference, wind1 and wind 3 simulations for an average hydro year.

tem is optimised by linear programming, using the total present value costs of the entire system over the whole study period as the objective function to be minimised. The study period is until year 2025, and it is divided into sub-periods (time steps) of 1–5 year each.

Two different scenarios were studied: ”Baseline” and ”Kyoto” up to the year 2025. In the Baseline scenario no emission reduction targets were set on greenhouse gas (GHG) emissions (i.e. Business-as-Usual scenario), and the development of the energy system is dependent mainly on the costs. This leads to large use of coal-condensing power due to its good competitiveness. One reason for this is the price of natural gas, which is assumed to increase nearly 100% from the present level during the study period. In the Kyoto scenario GHG emissions are stabilised to the 1990 level according to the Finland’s national Kyoto target. In this case it has been assumed that the use of coal-condensing power is nearly prohibited among other measures. Nuclear power production starts to decrease gradually around 2020 in both scenarios, and new capacity is not allowed. Hydro power capacity increases slightly during the study period, mainly due to renovations and new small-scale capacity. Maximum electricity imports are set to about 6 TWh/a in both scenarios. The background of the scenarios is described in more detail in (Kara et al. 2001).

Both scenarios were calculated at first by letting the model find the optimal level of wind power and other energy production technologies. Thereafter fixed scenarios for wind power production have been used to study the effects of increased wind power production on the energy system and CO_2 emissions, using the same levels as in the EMPS simulations, i.e. 1, 4 and 7 TWh/a in 2010 for Finland. The development of wind power production costs was given as input. Onshore production is limited to about 2 TWh/a in 2010 and about 3 TWh/a in 2025, due to e.g. land use restrictions. Offshore production is more expensive despite the fact that wind conditions are much better. It is assumed to be commercial in Finland after 2005. In the simulations with fixed wind power scenarios, the EFOM model finds a new optimum for the whole energy system.

In the Baseline scenario, wind power production remains quite low throughout the period as can be seen in Fig 6. In the fixed wind power scenarios (Base-Wind1 etc.), the incremental wind power replaces mainly coal-condensing power. Also small reductions in district heat and power production can be observed, especially in the use of natural gas combined cycle capacity (only some hundreds GWh/a). The GHG emissions will be reduced on the average about 680–700 g CO_2/kWh.

CO_2 abatement costs for wind power have been estimated by comparing the annual costs of the whole energy systems in different cases. For Base-Wind1 scenario the average emission reduction costs during 2010–2025 seem to be about 20 €/t CO_2. When the wind power capacity is further increased the average costs will raise gradually to about 35 EUR/t CO_2.

In the Kyoto scenario, wind power capacity increases quite remarkably in the cost-optimal case due to its competitiveness as an emission reduction measure. The use of coal-condensing power is minimised and consequently, when more wind power is added to the energy system, the new capacity replaces mainly natural gas combined-cycle (NGCC) capacity. The specific CO_2 emission reduction is only about 260–300 g CO_2/kWh due to the high efficiency of NGCC and other small changes in the energy system. It should be noticed that in the Kyoto scenarios the average CO_2 emission from electricity production is much lower than in the Baseline scenarios, and consequently the achievable emission reduction are clearly lower. As absolute emission reductions are significantly lower, also the specific emission reduction costs increase to about 40–60 €/t CO_2. This way of studying the abatement of wind power neglects the initial CO_2 abatement of the gas plant to the system, as well as the cost effective wind power already implemented in the base simulation. This actually reflects the situation in the future, when there is no more coal to be replaced, but the replacement will be gas.

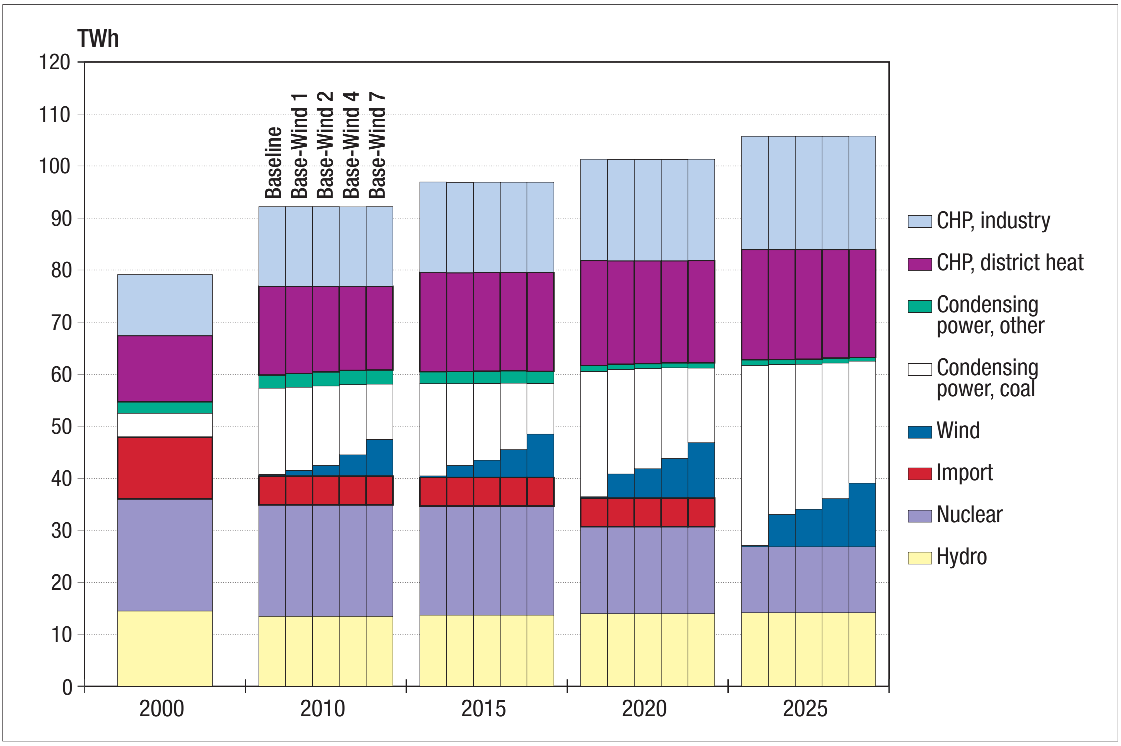

Figure 6. Total electricity supply in the Baseline scenario with different wind power production levels.

4 Conclusions

Finnish industry has a strong position in the wind power markets: generators, gear-boxes, blade materials, steel plates for towers and large castings are made in Finland, with a 10–20% global market share. In 2001, the Finnish exports of wind technology amounted to 0.2 billion €. A new Finnish wind turbine manufacturer, WinWinD, erected their first 1 MW prototype in 2001. The Finnish wind power technology industry already forms a technology cluster. By networking, the companies could have more export possibilities, for example the blade technology, control systems, tower components and offshore foundation techniques.

Increasing the size, control and intelligence in all the components of a wind turbine are the most significant technology trends in the near future. The building of large offshore wind farms will start. From the viewpoint of Finnish wind power component industry, more and more special know-how will be required. The solutions based on the concept chosen by the wind turbine manufacturer have to be taken into account from the beginning, when developing, designing and optimising the components.

Wind power is growing fast. The total installed capacity at the end of 2001 was about 24 GW, of which 17 GW in Europe. At the moment, the global market for wind power is about 6 billion € (6 GW annually). The growth rate is expected to stay high. When estimating the future potential of Finnish wind technology exports, the market estimates of 25 and 15 GW annually in 2010 have been used. If the Finnish industry is able to maintain the current market shares, the exports will be 0.8–1.2 billion € in 2010. If the Finnish wind turbine manufacturer were able to get a global market share of 5%, this would more that double the Finnish exports.

The fast growing wind power market is abroad. To stay there, or get there as a newcomer, requires more and more national support in the form of R&D and a home market.

The effect of wind power to the CO_2 abatement was studied by simulating the Nordic and Finnish energy systems with and without large scale wind power production. Results from the simulations show that wind power replaces mostly coal condense and oil as fuel for electric boilers. Reductions do not occur in the same countries as the wind production, e.g. coal condense is replaced also in Central Europe. As a result of adding wind to the simulated system, CO_2 emissions will be reduced 700–650 gCO_2/kWh. The same result applies for simulations for Finland. In a scenario, in which it has been assumed that coal condensing power is prohibited in order to meet the Finnish Kyoto target, new wind power capacity replaces the need for new natural gas combined-cycle capacity leading to CO_2 abatement of about 300 gCO_2/kWh. This case reflects the situation in the future, when there possibly is no more coal to be replaced.

The costs for CO_2 abatement by increasing wind power capacity in Finland seem to be about 20 €/t CO_2 for the first TWh of wind, and when the capacity is further increased the costs also raise gradually to 35 €/t CO_2 for the 7th TWh of wind. In the Kyoto scenario the achievable CO_2 abatement is clearly lower and therefore the costs are higher: 40–60 €/t CO_2.

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Publications and reports made under the project

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Road-Map for Solar Energy Technology and Markets in Finland

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SOLPROS

Abstract

The National Climate Strategy of Finland from spring 2001 and the Programme Promoting Renewable Energy Sources as part of it from 1999 define the national targets for renewable energy utilization and development in Finland up to year 2010. Solar energy is part of the above-mentioned national programmes.

The national target for solar energy utilization by year 2010 is 100 GWh/y. Moreover, taken the strong market growth of solar energy internationally, new business should also be generated. The domestic market is considered important in helping to commercialize new technologies and products.

The objective of the development project "Road-map for solar energy technology and markets in Finland" (abbr. Solar Road Map) was to prepare an action plan to the national solar energy targets and to show the way to reach the challenging goals mentioned earlier. The project was part of the Climtech programme of the National Technology Agency (Tekes).

The action plan for solar energy developed in this project captures on the market possibilities both on a national and international level. The action plan is based on a road-map in which different activities are undertaken stepwise to achieve the milestones set and the end goal. Different market driven activities and technology development have been combined to yield market breakthrough for solar energy. By year 2010 solar energy should be competitive on the national market, and the national industries should have reached a strong position on international markets. The goal of business generated by the action plan is 150 million euros/y by 2010.

The reduction potential of greenhouse gas emissions by solar energy is still small in Finland within the coming ten years, but on a longer term the possibilities will increase and also the costs associated show a positive trend.

Tiivistelmä

Kansallisessa ilmastostrategiassa keväältä 2001 ja uusiutuvien energialähteiden edistämisohjelmassa vuodelta 1999 on esitetty kansalliset tavoitteet uusiutuvien energialähteiden käytölle Suomessa vuoteen 2010. Aurinkoenergia on osa näitä ohjelmia.

Aurinkoenergian hyödyntämisen tavoitetaso vuonna 2010 on 100 GWh/v. Ottaen huomioon aurinkoenergian voimakkaasti kasvavat maailmanmarkkinat tulisi kansallisten toimien myös luoda uutta vientitoimintaa alueella. Kotimaan markkinat ovat tärkeät uuden teknologian kaupallistamisessa.

”Road-map for solar energy technology and markets in Finland” (lyh. Solar Road Map) yritysprojektin tavoitteena oli laatia toimenpideohjelma kansallisten aurinkoenergiatavoitteiden saavuttamiseksi. Hanke oli osa Tekesin Climtech-ohjelmaa.

Tässä projektissa laadittu aurinkoenergian toimenpideohjelma tarttuu niin kansallisten kuin kansainvälisten markkinoiden antamiin mahdollisuuksiin. Toimenpideohjelma on rakennettu ns. road map -muotoon, jossa ensin asetetaan välitavoitteet lopputavoitteesta käsin ja luodaan sen jälkeen toimintapolku toimenpiteineen alusta loppuun väli- ja lopputavoitteiden saavuttamiseksi.

Toimenpideohjelmassa on yhdistetty erilaisia markkina- ja teknologiapohjaisia toimia. Vuoteen 2010 aurinkoenergian tulisi olla kilpailukykyinen kansallisilla markkinoilla ja suomalaisen teollisuuden kilpailukykyistä kansainvälisillä markkinoilla. Alan liiketoiminnan määrässä tähdätään vuonna 2010 tasolle 150 milj. euro/v.

Tämän vuosikymmenen aikana aurinkoenergian merkitys Suomen kasvihuonepäästöjen vähentämisessä on pieni. Pitemmällä aikavälillä mahdollisuudet kasvavat ja lisäksi päästöjen vähentämiskustannukset aurinkoenergian avulla tulevat pienenemään.

1 Introduction

The National Climate Strategy of Finland from spring 2001 and the Programme Promoting Renewable Energy Sources (MTI 1999) as part of it from 1999 define the national targets for renewable energy utilization and development up to year 2010 and set indicative goals for the year 2025. Solar energy, both solar heating and photovoltaics, is part of the above-mentioned national programmes.

The national target for solar energy utilization by year 2010 is 100 GWh/y. Moreover, taken the strong market growth of solar energy internationally and the knowledge base of Finnish industries, the national programmes should generate new business worth 150 million euros by 2010 mainly for export markets. The domestic market is considered important in helping to commercialize new technologies and products.

The objective of the development project “Roadmap for solar energy technology and markets in Finland" (abbr. Solar Road Map) was to prepare an action plan to the national solar energy targets and show the way to reach the challenging goals mentioned earlier. The project was part of the Climtech-programme of the National Technology Agency (Tekes). The aim of Climtech has been to analyze the possibilities and development needs of technologies for climate change mitigation and to support the commercialization of associated Finnish technology.

The Solar Road Map project (2000–2001) was co-financed by Tekes and Solpros AY. Solpros did the realization. The project focused on analyzing the possibilities and development needs of solar energy in the light of the greenhouse gas emission reduction policies. The main technology areas of interest matching both national and international markets and their needs have been analyzed. Furthermore, areas important to strengthen Finnish industries have been identified. The project covered both solar heating and solar photovoltaics.

The Solar Road Map results comprise three major reports: a state-of-the-art review of solar energy technologies and markets, a review and analysis of solar energy and its possibilities in Finland and finally the action plan for solar energy (road map). In addition, the project resulted in establishing a national solar energy network and the Finnish Solar Industries working group (FSI).

2 International trends

2.1 Markets

Solar energy plays a negligible role in the present global energy system. Commercial solar energy utilization represents about 0.05% of world’s energy. On a local level, solar may have much more importance e.g. in providing heat to the buildings. In the coming 10–20 years, the use of solar energy will increase considerably, but it is not until the middle of this century that is could be recognized as an important energy source. Shell International has estimated in its energy scenarios that around 2060 solar energy could provide 30% of world’s energy. Going beyond that towards the end of the century, solar-hydrogen type of fuels could be an option for a global energy economy.

Solar energy is cost-effective in several niche applications and close to competitiveness in many applications in the built environment. Compared to bulk energy production by traditional energy sources, solar energy will necessitate public support. From an environmental point of view, solar energy represents one of the best alternatives.

2.1.1 Photovoltaics

The total worldwide installed capacity of photovoltaics (PV) is over 1 500 MW_p and the production capacity is now about 350 MW_p/y. The growth of the market has been more than 30%/y over the last five years. The global PV business has a value of around 2 500–3 000 million euros/y, of which about half is from the PV modules. Some 70% of the markets are in the industrialized countries and 30% in less-developed countries. The main market segments are off-grid stand-alone PV applications and grid-connected PV. The latter segment has grown fast and e.g. building integrated PV is becoming very important for the PV industries. In Europe, the German market is the largest one. In 2001, about 75 MW_p was installed and the German market grew by 45%. The Finnish PV market is about 0.1% of the global PV market.

EU's goal is to increase the use of PV by 500 MWp in EU countries and by 500 MWp in developing countries. This would mean that 2% of all new buildings in EU would have a PV system. Taking a slightly lower growth estimate of 15%/y for PV would mean a business potential of 8 000–12 000 million euros/y and a production capacity of 600–900 MW_p/y in 2010. Most of the growth is anticipated to come from PV in buildings. This PV segment is not yet competitive with grid electricity and would hence need public support. Several industrialized countries have major programmes to support PV integration into buildings. The market value of identified programmes is closer to 3 000 MW_p.

2.1.2 Solar heating

The solar collector area installed worldwide corresponds to about 20 TWh/y. In Europe, some 10 million m^2 of collectors are in operation representing 3–4 TWh/y. Swimming pools and domestic hot water represent about 90% of all solar heating.

The European solar heating market grows in average 15% per annum. The major market area is central Europe and in particular Germany. The German market has grown more than 30%/y over the last years, and the annual sales are around 1 million m^2 of collectors. The solar heating business in Germany corresponds to about 700 million euros/y. Germany and Austria alone represent over 60% of the EU market, South Europe some 25%, but northern Europe less than 10%. For comparison, the Finnish solar heating markets are less than 0.1% of the present EU market.

The medium-term market trends for solar heating in Europe are positive. The EU goal for solar heating in year 2010 is 100 million m^2 of installed capacity, which would require a 35% annual market growth. Based on present trends, 50–80 million m^2 seems to be more likely. Ordinary business growth

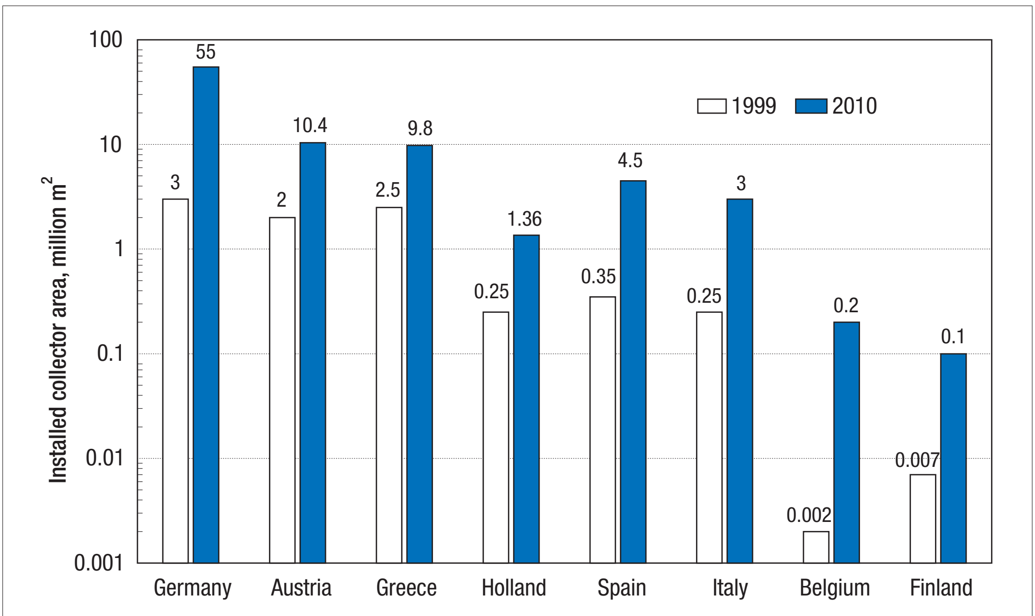

Figure 1. Solar heating market in selected EU countries in 1999 and 2010.

is around 15%/y which would mean a sales volume of 5 million m^2/y in 2010, or, a business value of 2 000–3 000 million euros/y. Figure 1 illustrates the market trends in Europe.

2.2 Possibilities of technology developments

Solar energy is a strategic innovation, which starts with a small market share (e.g. niche). If the vision materializes then this niche will grow on a long-term into prevailing business. Solar energy is thus in the beginning of its life cycle, in which developing and commercializing the technology plays a major role. Dropping the price of solar energy (or increasing its value), finding more economic applications and improving the competitiveness, are the major challenges for solar energy ahead.

For Finland, solar energy is on a short/medium term a technology driven export possibility. Even a small domestic market may support the development of industries and create competitive advantage through learning by doing and learning by using. In the following, we have summarized key technology development areas.

In addition to direct process or technology innovations, one may recognize the possibilities of indirect technology development as well: balance of system technologies; impact of other technology trends; technology synergies (e.g. building, information technology), or utilization of existing infrastructures (e.g. building, information networks).

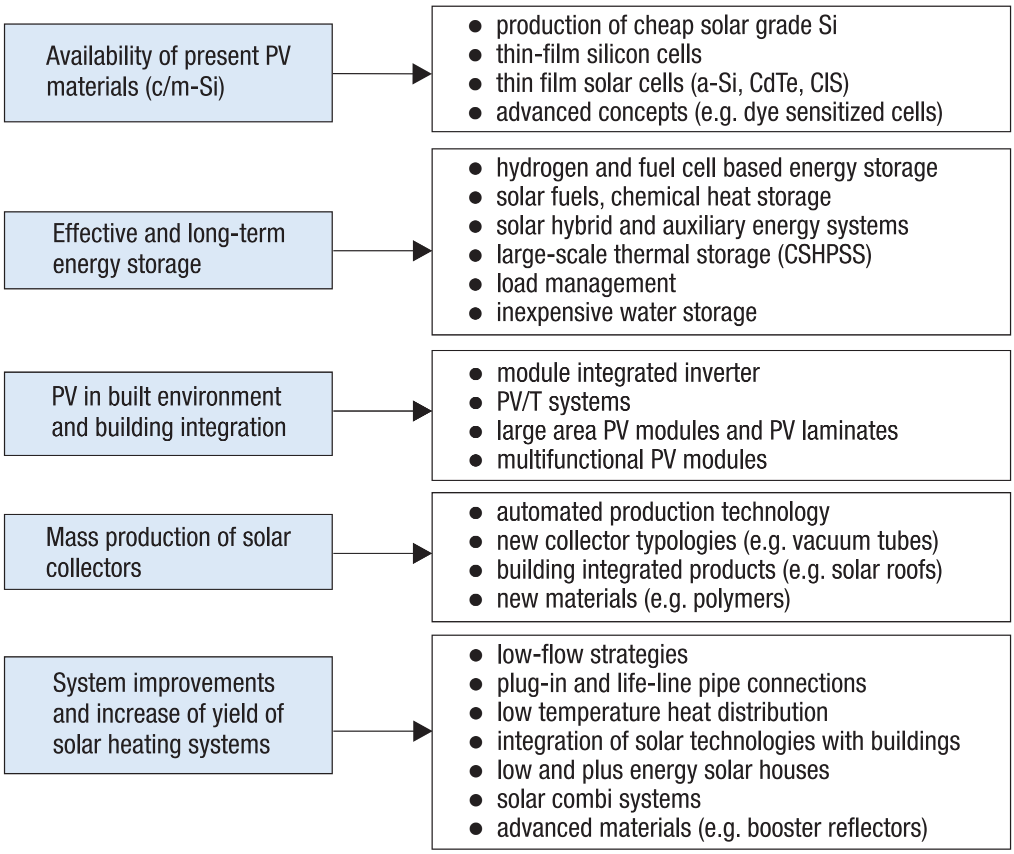

Figure 2. Key technology areas for solar energy.

3 Solar energy in Finland

3.1 Solar conditions and utilization in Finland

The solar insolation in southern Finland corresponds on an annual level roughly to that of central Europe (see Figure 3), or, 1000 kWh/m²/y on a horizontal surface. On an inclined surface, up to 1 100–1 200 kWh/m²/y may be expected. The seasonal variation of solar radiation in Finland is much larger – 90% of solar radiation is obtained between March and September.

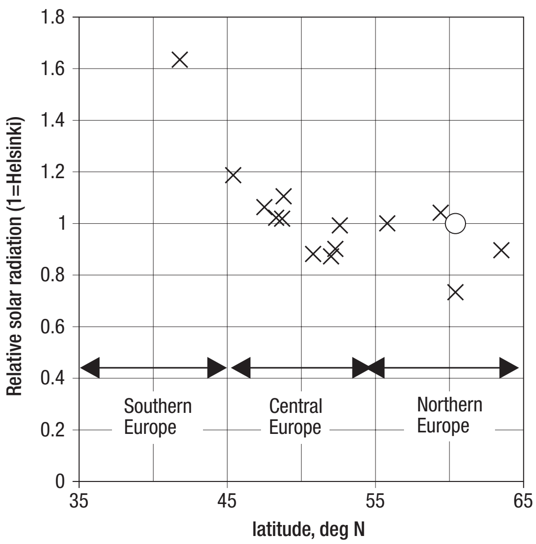

Figure 3. Yearly solar insolation on a 30° inclined south-faced surface (1=Helsinki).

The total amount of solar collectors in houses in Finland for domestic hot water and heating is about 10 000 m², which corresponds to about 3 GWh/y. In addition, there are some 70 000 m² (10 GWh/y) of simple unglazed air collectors used for crop drying.

The installed photovoltaics are 2.8 MW_p (2 Gwh/y). 95% of this are off-grid PV systems in summer houses, 5% are on-grid building integrated systems.

3.2 Project examples

One of the major recent solar energy projects is in Ekoviikki, Helsinki (Faninger-Lund 2000). The Ekoviikki area is an ecological suburb, a unique demonstration project for ecological and sustainable housing. The site includes the major solar projects in Finland. The largest solar heating systems with 8 subsystems of a total area of 1 246 m² solar collector area were built in 1999–2001. In 2002, a 24 kW_p building integrated PV system will be mounted on one apartment house. The PV panels will form a part of the balcony structures. Along with other PV systems the total expected PV capacity in the area would be 35 kW_p. Building integration of the solar panels has been important in Ekoviikki.

Another unique Finnish project on long-term is solar energy storage, in which hydrogen technologies have been used with PV to provide 100% electricity over the year.

Figure 4. Left: One of the solar heating systems (solar roof) in Ekoviikki. Right: PV balcony in Ekoviikki.

Figure 5. Solar hydrogen systems developed in Finland for stand-alone remote applications.

3.3 Cost of solar energy

The rate and magnitude of market penetration of solar energy is very much dependent on its costs. Excluding niche markets and some narrow market segments, solar energy in Finland is not yet fully competitive against traditional energy sources and fuels.

The cost of solar heat at present is around 0.1 euros/kWh. By year 2010, the price could drop to 0.05 euros/kWh. The economic conditions and requirements (life-time, interest rate) have an influence on the solar cost as shown in Figure 6. If viewing solar as part of the building or as a building component, then a lower interest rate may be justified and the cost of solar would be 0.07–0.08 euros/kWh.

A special category is large-scale solar heating applicable for larger heat loads (>300 MWh/y). Here 0.05 euros/kWh or even less is possible already today.

Table 1 shows how different factors may influence the price of solar heating.

In case of photovoltaics, the present system cost is around 6.5–8 euros/W_p and year 2010 goal is under 4 euros/W_p. The theoretical lifetime of a PV module may be 40–50 years, as it does not have any moving nor mechanical parts. Cost of on-grid PV electricity is around 0.6–0.8 euros/kWh, for stand-alone off-grid systems with battery the cost is 0.8–1 euros/kWh. If PV is a part of the building structure (e.g. solar roof) and modest economic return is required, the cost of PV electricity is around 0.20 euros/kWh. In 2010, a 0.1–0.3 euros/kWh price level is anticipated (Figure 8).

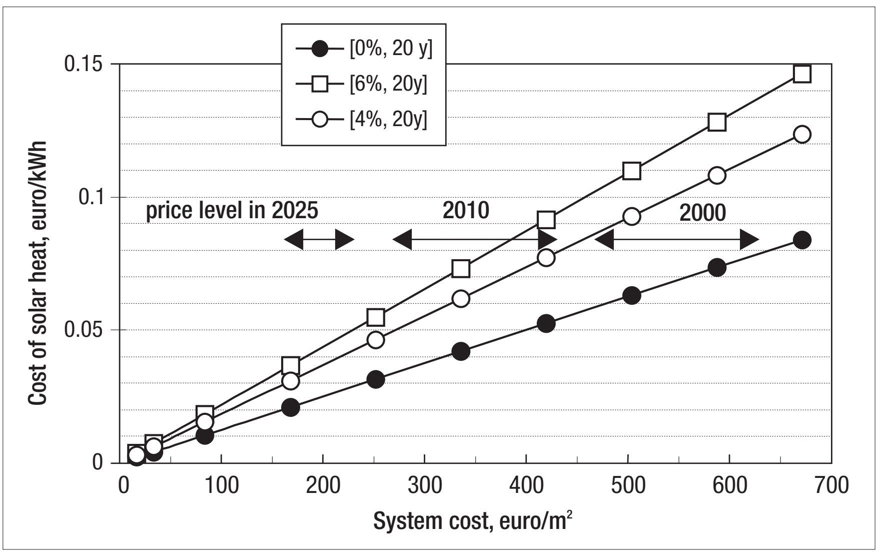

Figure 6. Cost of solar heat in Finland with different economic parameters and system costs.

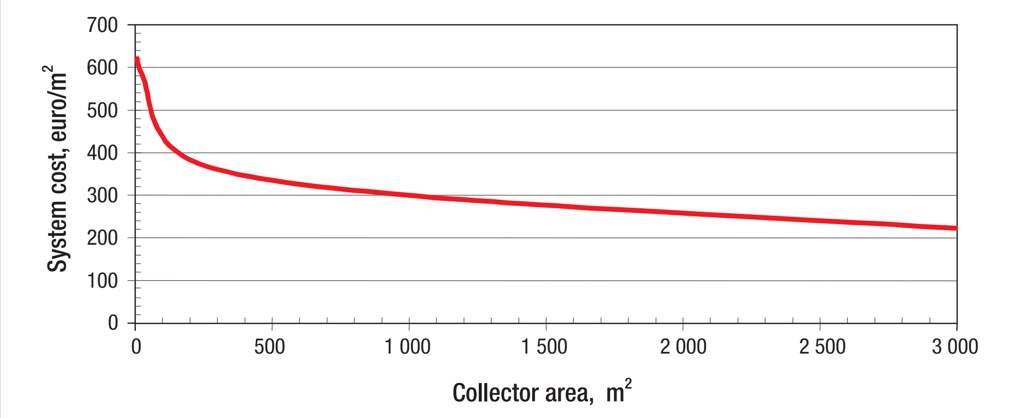

Figure 7. Present system cost of solar heating systems versus system size.

Table 1. Estimate of cost reduction in solar heat through different factors.

Price factor	Cost effect	Actions needed
Practical experience in planning, mounting and projects	10–20%	Information, training, increased volumes
Standardized system solutions	10–20%	Competition, increased volume
Logistics	10%	Cooperation
Technology development, influence of international markets	20–30%	Technology transfer, international cooperation

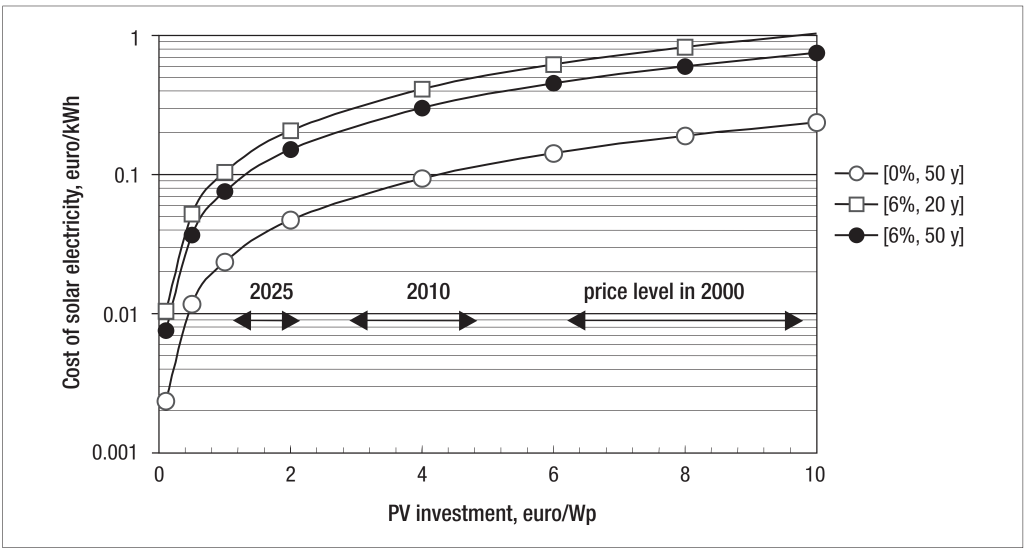

Figure 8. Cost of solar electricity in Finland with different economic parameters and system costs.

3.4 Near future market potential

Without public support, the solar energy markets in Finland are very limited. Commercially viable applications could be found in different niches, such as PV for summer cottages and remote applications and solar heating for low-temperature summertime uses, e.g. for camping areas. The total size of these niches for solar heating is about 20 GWh/y corresponding to 50 000 m^2 of solar collectors, and for PV we find 10 MW_p or 10 GWh/y.

The Ministry of Trade and Industry has updated in July 2002 the investment subsidies for renewable and new energy technology. Accordingly, solar energy applications will now receive an investment subsidy up to 40% of the total investment. With the existing subsidy, which is mainly meant for municipalities and companies, the near term market potential for solar heating is increased to 1 490 GWh/y (3 800 000 m^2) and PV to 100 GWh/y (100 MW_p). The potential would even grow if private householders would receive public support for their solar energy investments.

The maximum or long-term potential of solar energy in Finland has been estimated as follows: photovoltaics in buildings 5 500 GWh/y and solar heating 4 000–5 000 GWh/y.

4 Action plan for solar energy

4.1 Road Map

Based on the international trends and markets, national state-of-the art of technology and market potential, and the national goals set for solar energy, a road map has been built for solar energy in Finland. The road map is a path in which milestones are defined starting from the end. To reach the milestones, measures are set moving from start to the end.

Table 2 summarizes the key goals set in the action plan for solar energy.

The need of public support for the action plan over 2001–2010 is in total 25 million euros.

The road map for solar energy in Finland is illustrated in Figure 9.

Table 2. Strategic goals of the action plan for solar energy.

GOALS FOR THE ACTION PLAN ON SOLAR ENERGY			
Year	**Strategic goal**	**Turnover**	**Use of solar energy in Finland**
2010	Solar energy is fully on the Finnish market Leading position in certain market segments	150 M€/y	100 GWh/y
2008	Established markets in Finland Significant export in EU and LDCs	100	45
2006	Solar energy is clearly on the domestic market Export grows in the EU	40	20
2004	Solid growth of the national solar market New export activities established	15	15
2002	Introduction of solar energy on the Finnish market Improvement of existing technologies		

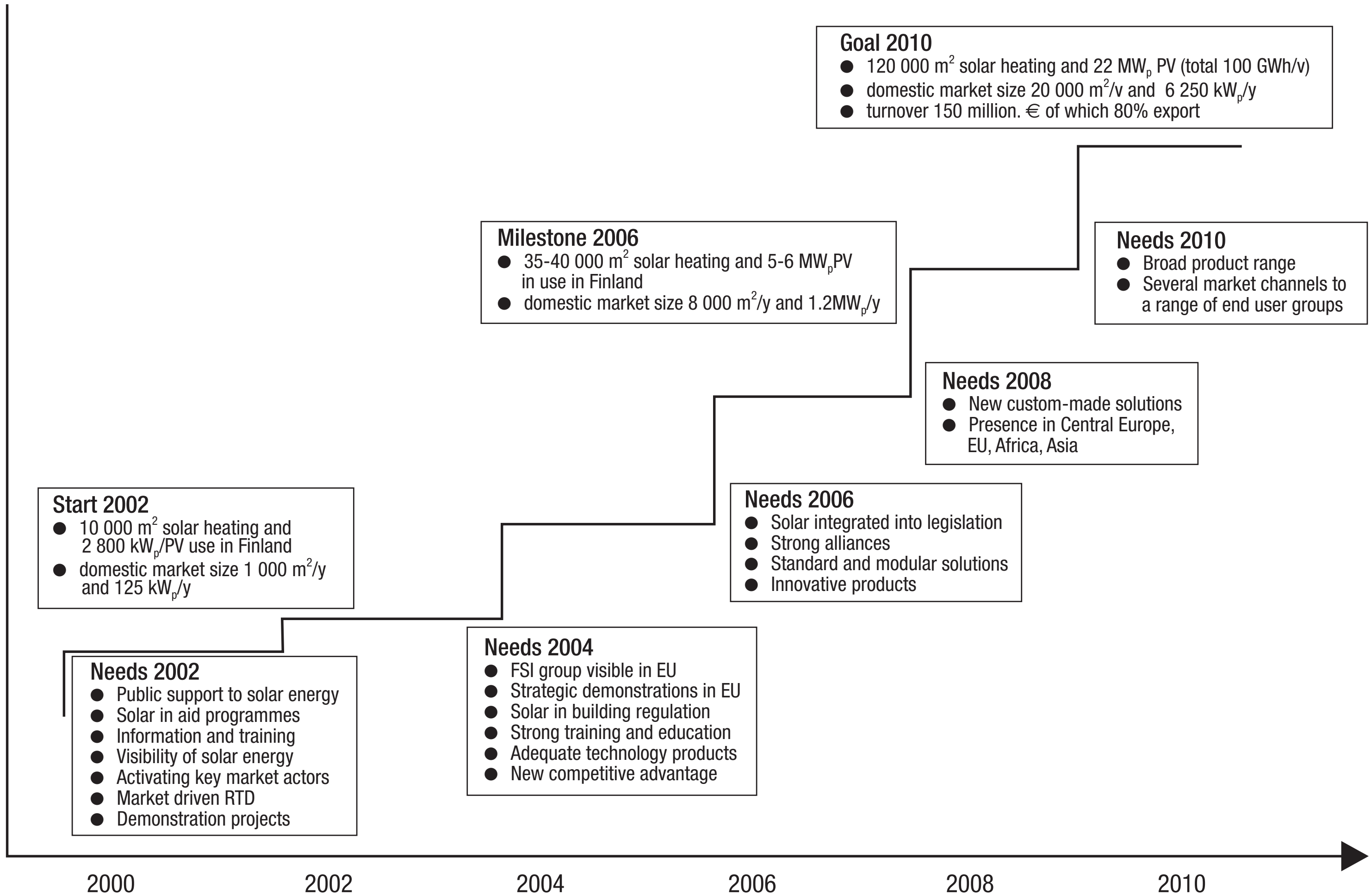

Figure 9. The road map for solar energy in Finland.

4.2 Finnish Solar Industries

One important outcome of the project has been the establishment of the Finnish Solar Industries (FSI) working group, which comprises strategic market actors (industries, authorities, experts). FSI has acted as a support to the present project, but will also be an important actor group in realizing the action plan in practice. The activities of the FSI are focused on areas that give clear added value to the participants such as sharing common information, joint activities to open the markets, influencing standards and norms, increasing the commitment and continuity in solar development, joint representation at fairs and international events, etc.

Also, FSI promotes business concept innovations where the traditional technology development as source for innovation is broadened to include service/channel and customer target groups as well.

FSI is part of the national solar energy network established in parallel. Both networks have now about 30 organizations represented. FSI and national solar network are coordinated by SOLPROS.

4.3 First actions in year 2002

The action plan starts in 2002 and it will be open to all interested market actors. The structure at this stage is virtual and the network of actors and their activities form the core of the practical programme realization. The authorities support the activities case by case. Thus, the outcome from the action plan is very much dependent on how active the solar field itself is.

The action plan concentrates on two major segments, namely solar heating and photovoltaics. First projects are focused on activities in which solar energy gives the best added value.

Another important objective in 2002 is to increase the number of industries and key market actors in the solar programme. Cooperation is important. The Finnish Solar Industries group and solar network are seen as an important tool and asset. Training and education modules will be planned together with regional and national energy agencies.

4.4 End goal in 2010

The end goal of the action plan for solar energy is that solar energy is competitive on the national market in 2010 and that Finnish industries are strongly established on the global market.

The solar utilization in Finland would correspond to about 100 GWh/y (e.g. 120 000 m^2 solar heating and 22 000 kW_p PV)

4.5 Impact of solar energy on GHG emissions in Finland

If the action plan meets its goal, solar energy will reduce the greenhouse gas emissions in Finland by 0.02–0.04 million tons of CO_2 in 2010. In 2025, the impact could be 0.3–0.7 mill. t CO_2 Solar heat replaces mainly light fuel oil and PV coal fired condensing power or average electricity mix.

The CO_2 reduction cost using solar energy is at the moment well over 100 euros/ton CO_2. In 2010, the cost may drop down to 10–40 euros/ton CO_2 for solar heat and 100–400 euros/ton CO_2 for PV. In the long-term run by 2025, the cost could turn negative (Figure 10).

5 Conclusions

An action plan for solar energy for Finland to meet the goals set in the National Climate Strategy and the Programme Promoting Renewable Energy Sources has been prepared. A road-map type of approach has been used.

The action plan includes specific actions and milestones during 2002–2010. The first challenge is in starting the implementation of the plan and in opening the solar energy market in Finland. The plan recognizes networking and cooperation between market actors and different target groups as key elements in practical implementation. The Finnish Solar Industries (FSI) working group consisting of strategic market actors was established to support the plan. In addition, a national solar energy network has been initiated.

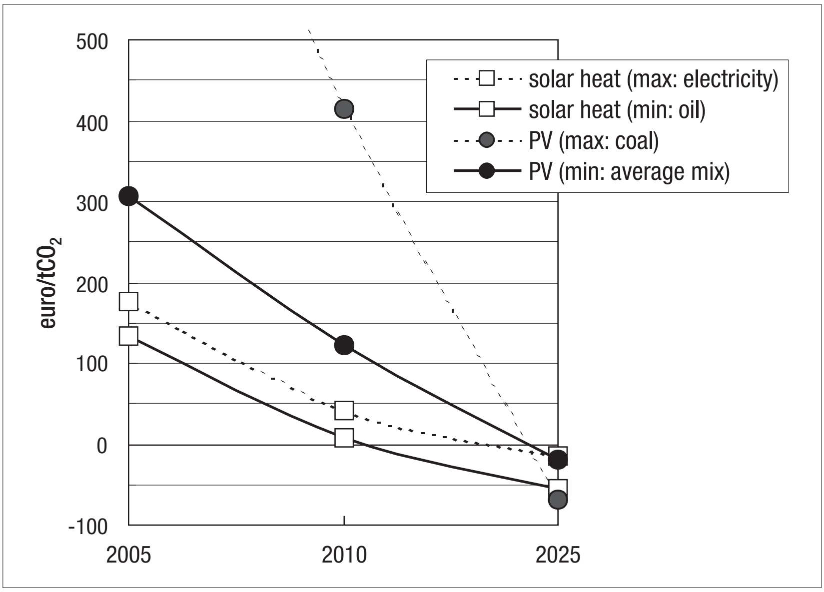

Figure 10. Cost of CO_2 reduction using solar energy in Finland.

The end goal of the action plan is 100 GWh/y solar energy in Finland and 150 million euros/y turnover by 2010. These are about 10-fold compared to present situation. The analyses done show, however, that with the mechanisms of public support, which are nearly in place, the market potential for solar energy based on costs is much larger than the targets set. This and international trends give confidence that the challenging goals can be met.

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The Possibilities of Bioenergy in Reducing Greenhouse Gas Emissions

Bioenergian mahdollisuudet kasvihuonekaasupäästöjen vähentämisessä

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Abstract

The use of bioenergy can be increased in existing and planned plants in industry, district heating and residential buildings according to the National Action Plan for Renewable Energy Sources and Climate Strategy, the target of which is 7.8 Mtoe in 2010. Compared to 1999, the growth is 1.2 Mtoe, 50% of which will be in industry, 40% in residential heating and the rest in district heating. Power production would increase 3 TWh compared to 1999. The potential reduction of carbon dioxide emissions would be 2.8–3.7 million ton CO_2 compared to 1999 when replacing fossil fuels. Forest residue from regeneration fellings and waste used in existing plants have the lowest costs of energy production. Additionally, the increased use of wood fuels, like pellets or bio-oils for residential heating, is economically competitive.

With small additional investments to existing plants and use of biofuels with higher costs, the use of bioenergy could reach 9.5 Mtoe in 2010. The increase would be especially viable in the district-heating sector. Power production with biomass would increase 6 TWh compared to 1999, but the increase of the power production capacity would not be significant. The potential reduction of carbon dioxide emissions would be 7.4–10.9 million ton CO_2 compared to 1999. The estimate does not include reduction of greenhouse gas emission based on the reduction of landfill gases when using waste.

Before 2025, most CHP plants shall be replaced with new plants, which would enable to install plants with new technologies. The most promising opportunity is CHP technology with high power-to-heat ratios in all classes of capacity, which would double the power production capacity per existing heat lead compared to the present situation. The potential for additional power production from biomass in 2025 would be 10 TWh compared to the level of the year 2010.

Investments needed for R&D, timetables for commercial implementation and market volumes in Europe are estimated for each of the new technologies in the fields of fuel and energy production. The Finnish industry has a good position in the development of new technologies, because the traditions in the use of bioenergy are very long and Finland has good circumstances for demonstration projects. The exports of new products can reach during the following years the annual level of one billion euros.

Lyhennelmä

Bioenergian käyttöä voidaan lisätä nykyisissä ja suunnitteilla olevissa yhdyskuntien ja teollisuuden laitoksissa sekä kiinteistöjen lämmityksessä Uusiutuvien energialähteiden edistämisohjelmassa ja kansallisessa ilmastostrategiassa esitettyyn tavoitteeseen 7,8 Mtoe:iin vuoteen 2010 mennessä. Vuoden 1999 käyttöön verrattuna lisäys on 1,2 Mtoe, josta 50 % olisi teollisuudessa, 40 % kiinteistöissä ja loppuosa kaukolämmön tuotannossa. Sähkön tuotanto lisääntyisi vuoteen 1999 verrattuna 3 TWh. Hiilidioksidipäästöjen vähennysmahdollisuus vuoteen 1999 verrattuna olisi 2,8–3,7 milj.CO_2 tonnia korvattaessa fossiilisia polttoaineita. Edullisimmin voidaan lisätä uudistushakkuiden hakkuutähteiden käyttöä ja jätteiden energiakäyttöä nykyisissä laitoksissa. Myös puun ja sen jalosteiden käytön lisääminen kiinteistöjen lämmityksessä on taloudellisesti kilpailukykyistä.

Pienillä lisäinvestoinneilla nykyisiin laitoksiin ja käyttämällä tuotantokustannuksiltaan kalliimpia biopolttoaineita voitaisiin käyttöä lisätä jopa 9,5 Mtoe:iin vuoteen 2010 mennessä. Käytön lisäys olisi tällöin erityisesti kaukolämmityksen tuotan-

nossa. Sähkön tuotanto biopolttoaineilla lisääntyisi vuoteen 1999 verrattuna lähes 6 TWh, mutta sähkön tuotantokapasiteetti ei kasvaisi merkittävästi. Hiilidioksidipäästöjen vähennysmahdollisuus vuoteen 1999 verrattuna olisi 7,4–10,9 milj. CO_2 tonnia. Arvioissa ei ole otettu huomioon jätteiden energiakäytön aiheuttamaa kaatopaikkojen kasvihuonekaasupäästöjen vähenemistä.

Vuoteen 2025 mennessä monia sähköä ja lämpöä tuottavia laitoksia on korvattava uusilla, mikä mahdollistaisi uuden tekniikan laajamittaisen käyttöönoton. Merkittävin mahdollisuus sisältyy uuden korkearakennusasteisen CHP-tekniikan käyttöönottoon kaikissa kokoluokissa, jolloin sähkön tuotantokapasiteettia saadaan nykytilanteeseen verrattuna kaksinkertaisesti olemassaolevaa lämpökuormaa kohti. Sähkön tuotantomahdollisuus biopolttoaineilla kasvaisi noin 10 TWh vuoden 2010 tasoon verrattuna.

Kehitteillä olevista polttoaineiden ja energian tuotannon tekniikoista on arvioitu tarvittava panostus, kaupallistumisaikataulu sekä markkinoiden laajuus Euroopassa. Suomalaisella teollisuudella on uusien tekniikoiden kehittäjänä hyvä asema, koska biopolttoaineiden energiakäytöstä suomalaisella tekniikalla on vuosikymmenien perinteet ja Suomi tarjoaa hyvät puitteet uusien tekniikoiden demonstrointiin. Uusien tuotteiden vienti voi jo lähivuosina kohota miljardiin euroon vuodessa.

1 Introduction

The National Action Plan for Renewable Energy Sources (MTI 1999) and Climate Strategy (MTI 2001) have set the target to increase the use of renewable energy sources (RES) by 50% in the period 1995–2010. 80% of the increase would be covered by bioenergy. RES would correspond to 27% of the primary energy consumption and 31% of the electricity production in 2010.

The aim of this study is to update and improve the information concerning bioenergy that was given in the background report of the National Action Plan (Helynen et al. 1999). The possibilities of the present technology and its costs by 2010 are described, and possibilities of the new technologies up to 2025 are estimated. Research and development demands and potential markets of new technologies are identified. The potential reduction of greenhouse gas emissions is calculated based on the replacement of fossil fuels.

2 Biomass resources

The present use of bioenergy is dominated by residues and by-products from the forest industry (Table 1). Also the use of firewood is significant. The use of harvesting residues and waste has recently started.

Table 1. The use of bioenergy based fuels in Finland in 2000.

	Mtoe	TWh	Share of the energy consumption in Finland
Black liquor	3.4	40	11
Solid biofuels, of which	2.0	23	6
• bark	1.2	14	
• saw dust, etc	0.4	5	
• logging residues	0.1	1.5	
Fire wood	1.1	13	3
Wood fuels, total	6.5	76	20
Waste	0.02	0.28	
Biogas	0.02	0.2	
Peat	1.4	16	4

The availability of different biomass resources are estimated for 15 areas of Finland for six types of biomass based fuels that have different cost levels (Tables 2 and 3). Two different scenarios have been created. The Basic Scenario introduces the situation with continuation of the present policy including promotion activities of RES. The Maximum Scenario is connected to the improvement of competitiveness of bioenergy, which could allow a cost increase of 50% on fuel compared to the present situation. Also the availability of peat is introduced because it can smooth variations in the availability and quality of biomass based fuels.

Residues of the forest industry, such as bark and saw dust, are presently utilised totally. Their future amount will depend on the volume of production level that can grow slowly because the growth of forests is still increasing. Annual changes of the production level are significant, which has a great effect on the availability of residues in the fuel market.

Harvesting residues from spruce dominated fellings and waste are the greatest low-cost biomass reserves for energy production. Residues from thinnings and agrobiomass, such as straw and reed canary grass, have higher production costs. Biomass-based fuels resulted from waste handling are studied in a report (Lohiniva et al. 2002) written in close conjunction with this study.

Biomass resources are not located evenly geographically. Residues from the forest industry are naturally adjacent to mills, harvesting residues to forests and their logging operations, agrobiomass to the fields and waste to urban areas. Another important factor is the close distance between biomass resources and heat demands, such as district heating networks and industry.

Import and export possibilities are most viable in the coast of Finland. The market volumes have so far been quite limited, below 1 TWh annually, but they are increasing. Especially refined fuels, such as pellets, allow longer transportation distance and long-term storage. About 80% of the pellet production has been exported to Sweden, Denmark and other European countries. Wood chips are imported by trucks from Russia, where cheap return transportations have been utilised.

Table 2. Availability and costs of biomass-based fuel (without black liquor and fire wood) in the Basic Scenario.

	2010 TWh/a	2025 TWh/a	Average cost level €/MWh
Residues and by-products from forest industry	20.5	22.6	5–6.7
Harvesting residues from spruce dominating fellings	4.9	4.9	6.7–9.3
Harvesting residues from pine dominating fellings	2.8	2.8	8.4–9.3
Thinnings and young stands	1.4	1.4	9.3–13.5
Wood fuels, total	29.7	31.7	
Waste fuels	5.0	5.0	n.a.
Agrobiomass	0	0	
Solid biomass based fuels, total	34.7	36.7	
Peat	22.8	22.8	

Table 3. Availability and costs of biomass-based fuel (without black liquor and fire wood) in the Maximum Scenario.

	2010 TWh/a	2025 TWh/a	Average cost level €/MWh
Residues and by-products from forest industry	23.6	27.1	5–7.6
Harvesting residues from spruce dominating fellings	7.2	7.2	6.7–10.1
Harvesting residues from pine dominating fellings	3.3	3.3	8.4–10.1
Thinnings and young stands	9.5	9.5	9.3–13.5
Wood fuels, total	43.6	47.1	
Waste fuels	10.0	10.0	n.a.
Agrobiomass	1.5	1.5	13.5
Solid biomass based fuels, total	55.0	58.5	
Peat	22.8	22.8	

3 Use of bioenergy with present technologies

Possibilities to use bioenergy have been investigated separately in 700 cases. They include large-scale consumers: district heating networks, industrial enterprises and others, and most of them presently use bioenergy. Existing energy production plants and their age and operation values have been collected, and changes for their future energy demands have been estimated. The use of fire wood has been calculated based on the estimations on building volume, specific energy consumption and the market share of wood firing as a supplementary or main energy supply.

In the Basic Scenario the use of biomass have been increased in plants where it is possible with existing equipment. New plants are built when old units are aging. Combined heat and power (CHP) plants and biomass boilers replacing oil burners are built when the heat demand is over the chosen limits. In the Maximum Scenario minor investments are carried out to maximize the use of bioenergy in the existing boilers. Seven pulverized coal boilers are used for co-firing with 2–3% biomass. Bioenergy is not estimated to replace economically natural gas in either scenarios.

In the Basic Scenario the use of bioenergy in 2010 is estimated to be the same as in the National Action Plan on RES (Figure 1). The increase of power production is quite modest, 3 TWh/a. Available bioenergy resources and demand are in balance in whole Finland but regional variations exist. The use of bioenergy in the Maximum Scenario is 20 TWh greater and the power production is 3 TWh greater than in the Basic Scenario in 2010 (Figure 2). Excess amount of available biomass is 12 TWh.

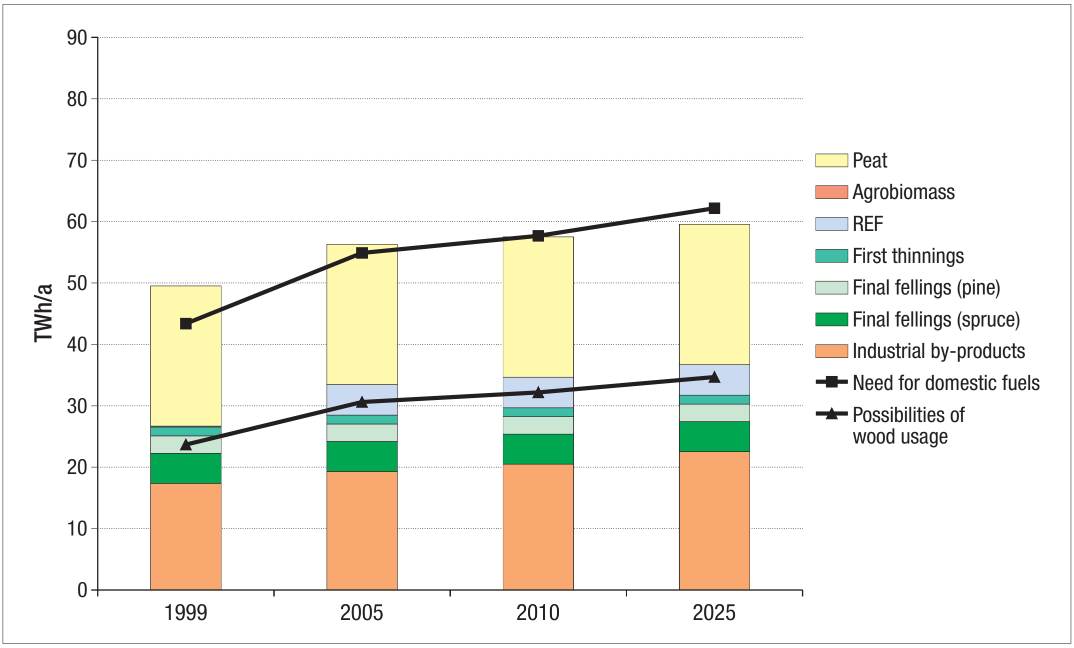

Figure 1. Potential use of bioenergy in large-scale use without black liquor, compared to the availability of biomass in the Basic Scenario.

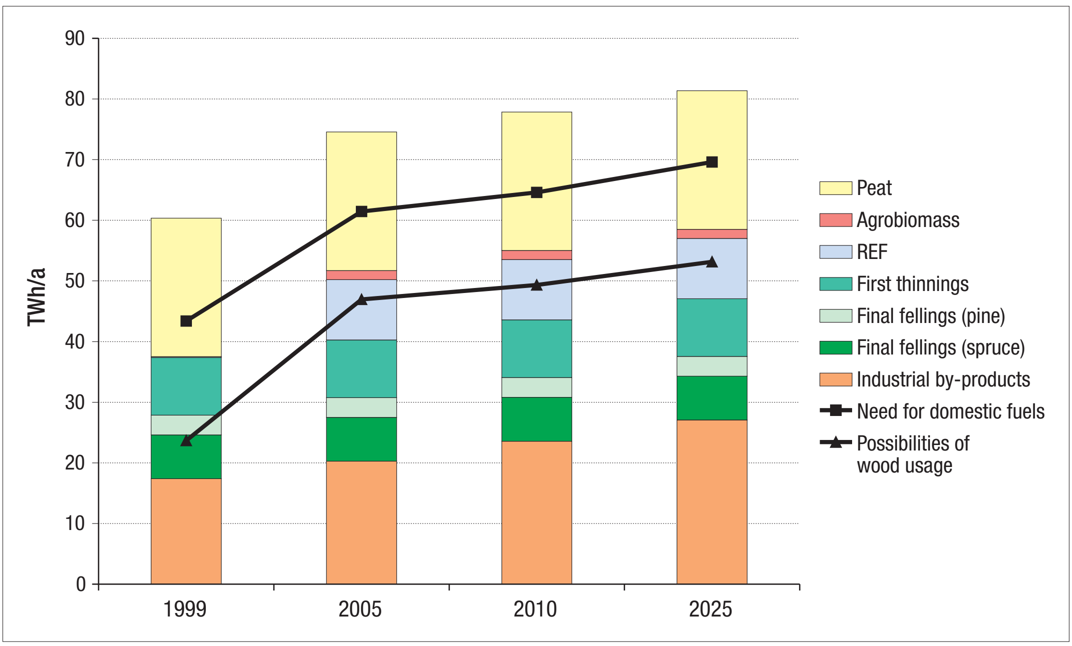

Figure 2. Potential use of bioenergy in large-scale use without black liquor, compared to the availability of biomass in the Maximum Scenario.

4 New technologies

The development of bioenergy technologies is connected to better competetitiveness that means better efficiency, higher power-to-heat ratios, and lower investment and maintenance costs. Of course, the reduction of emissions is still important, especially emission of fine particles and emissions from waste incineration.

4.1 Fuel harvesting and handling

The costs of biomass-based fuels can still be reduced significantly with modern harvesting, logistics and fuel handling systems. Drying and compacting of biomass reduces transportation costs and also the size of energy production equipment. Production of liquid biofuels also improves possibilities to deliver bioenergy to private customers, and even to use it in traffic.

4.2 Residential heating

The use of biomass, e.g. using wood logs, chips or pellets in residential heating (20 kW–1000 kW), is competitive compared to the use of light fuel oil (price level 40 €/MWh). However, wood is seldom chosen as the primary source of heating energy, because the investment costs are higher and more attention is needed for operation and maintenance than with oil heating. The development work is concentrated on those disadvantages of wood heating.

4.3 Small-scale CHP plants

In small scale, under 15 MWe, the following concepts will be available for CHP plants

1. Steam boiler and steam turbine/engine
2. Gasifier, steam boiler and steam turbine
3. Gasifier and combustion engine/gas turbine (Figure 3)
4. Flash pyrolyser and combustion engine/gas turbine
5. Stirling engine
6. ORC (Organic Rankine Cycle) turbine
7. Biogas reactor/landfill gas and combustion engine.

Gasifiers connected to combustion engine could provide higher power-to-heat ratios than the presently dominating steam boiler – steam turbine concept, if the product gas can be cleaned efficiently. Centralized production of flash pyrolysis use and its transportation to decentralized diesel engines

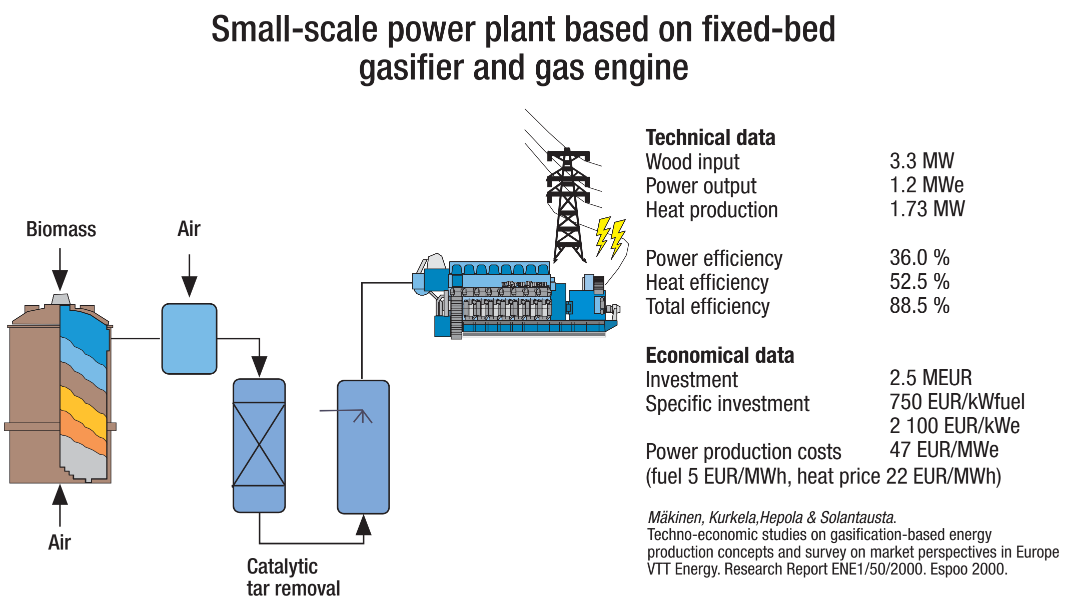

Figure 3. Fixed bed gasifier and combustion engine.

could also be competitive compared to present alternatives. Research work connected to fuel cells is increasing, but the use of biomass still requires several years of R&D.

4.4 Large-scale CHP plants

Co-firing of biomass in existing pulverized coal fired boilers has several concepts that need still more development work. Direct co-firing with existing equipment has typically limited the share of wood to less than 5%, but a special burner construction and modifications with fuel handling equipment can increase the share. High shares can be attained by means of boiler modifications to fluidised bed or by connecting a separate gasifier or boiler to the existing boiler.

The fluidised bed technology connected to high steam values can increase power-to-heat ratios (over 0.5) compared to conventional concepts. The pressurized fluidized bed combustion (PFBC) concept can achieve the ratio of 0.55–0.7, and the concept can be further improved by the topping cycle with partial gasification and pressurized combustion. Integrated gasification combined cycle (IGCC) could reach power-to-heat ratio of 0.8–1.2 in the capacity range of 40–100 MWe using solid wood fuels. The next phase of development work of IGCC is the large-scale demonstration plant. Pressurised gasification of black liquor will still need several years of intensive research and development work before commercial implementation.

5 Potential on reduction of greenhouse gas emissions

Biomass resources are ample in Finland, but alternative possibilities for the use of bioenergy with reasonable cost levels are even higher than the resources. If the price of electricity is high or the share of RES in electricity is increased, biomass will be directed to CHP plants, also in smaller capacity classes than before. If the CO_2 emissions are taxed in heat production or the price level of fossil fuels increases, oil will be replaced in the heating sector and coal will be replaced in coal fired CHP plants. Legislation can also require a significant share of biomass resources used for biofuels in the traffic sector.

The potential CO_2 reduction with bioenergy has been calculated assuming that light fuel oil is replaced in the residential heating sector. and alternatively natural gas or coal is replaced in the sectors of district heat and industry. In the next few years, the major increase in the use of bioenergy is anticipated to occur in CHP plants and in the heating sector (Table 4).

Table 4. Potential increase on the use of bioenergy by consumer sectors and its reduction potential on CO_2 emissions.

Consumer sector	Scenario	Potential addition of bioenergy use in 1999–2010, TWh	Reduction potential on CO_2 emissions, million tons
Residential heating	Basic Maximum	5.8 9.3	1.4 2.2
District heating	Basic Maximum	1.8 13.8	0.4–0.6 2.8–4.7
Industry	Basic Maximum	6.7 11.8	1.4–2.3 2.4–4.0
TOTAL	Basic Maximum	14.3 34.9	2.8–3.7 7.4–10.9
Available additional biomass	Basic Maximum	13 38	

6 Discussion

The potential of bioenergy has been analysed in two scenarios with several assumptions that have significant effects on the competitiveness. However, there are several aspects that have not been analysed and that may have great effects on the actual use of bioenergy. One of the major single factors in Finland is the production level of the forest industry, because forest industry presently covers about 80% of the use of bioenergy and provides about 80% of the biomass-based fuels in Finland.

In Finland, bioenergy resources are ample but not unlimited. Legislation and other international and national measures can dramatically guide how biomass is used: alone or in co-firing, or in heating, power production, production on refined fuels (pellets, briquettes, bio-oils) for private consumers or transportation fuels. Respectively, those measures affect the volume of bioenergy market and especially the volume of exports and imports. Possible major exporters in Europe include Baltic countries and Russia, but also tropic countries with high annual growths of biomass. High differences on price levels on fuel market in different countries can change the market situation dramatically.

7 Conclusions

The possibilities to increase the use of bioenergy by over 50% in 1999–2010 exist, and consequently potential reduction on CO_2 emissions is significant, 3–11 million tons of CO_2. The development of new technology is an efficient way to reduce the costs of that. New technologies are needed to allow high power-to-heat ratios in CHP plants, to make smaller CHP plants competitive and to provide low emission levels and to ease operation and maintenance for private consumer applications.

The year of commercial implementation, the need of development and demonstration work and the volume of commercial market in Finland and other countries are estimated for 24 bioenergy technologies (Table 5). The choice of the technologies is based on the facts that the development of technologies is important for Finland.

Table 5. Development programme for bioenergy technologies.

Technology, Power-to-heat ratio	Year of commercial implementation	R&D need and demonstration investments	Business volume in Finland and in other countries by 2010
Large-scale CHP			
Cofiring in pulverized coal boilers, 0.5	Before 2005	1–3 demonstrations, 2–10 M€/plant	FIN: 15 plants Europe: several hundreds
New fluidised bed boilers 0.5	Before 2010	1–3 demonstrations, 125 M€/500 MW boiler	FIN: 10 plants Europe: tens of plants
New recovery boilers 0.35	Before 2010	1–3 demonstrations, 85 M€/200 MW boiler	FIN: 5 plants Europe: tens of plants
Gasification of biomass and gas cleaning with waste fuels 0.5	Before 2010	1–3 demonstrations, 35 M€/100 MW gasifier	FIN: 10 plants Europe: tens of plants
IGCC 0.7-1.0	2010	1–3 demonstrations, 85 M€/100 MW (fuel)	FIN: 1–3 plants Europe: tens of plants

… Table 5. continues

Technology, Power-to-heat ratio	Year of commercial implementation	R&D need and demonstration investments	Business volume in Finland and in other countries by 2010
PFBC 0.7-1.0	2010	R&D, Demonstration 2005 125 M€/200 MW (fuel	FIN: 1–3 plants Europe: tens of plants
Pressurised gasification of black liquor	After 2010	R&D Demonstration phase by phase 2005-2010	
Small-scale CHP			
Grate boiler and steam engine/turbine 0.15-> 0.25	2005	1–3 demonstrations, 4 M€/2.5 MWe	FIN: tens of plants Europe: several hundreds
Fluidised bed boiler and steam turbine 0.3-> 0.4-0.5	2005	1–3 demonstrations, 7 M€/5 MWe	FIN: 10 plants Europe: several hundreds
Fixed-bed gasifier and gas-cleaning for combustion engine 0.6-0.8	2005	1–3 demonstrations, 3.5 M€/2 MWe	FIN: tens of plants Europe: several hundreds
Pyrolysis oil and combustion engine 0.6-0.8	2005	1–3 demonstrations, 3.5 M€/2.5 MWe	FIN: tens of plants Europe: several hundreds
ORC process	2005	1–3 demonstrations, 0.35 M€/0.2 MWe	FIN: tens of plants Europe: several hundreds
Fuel cells	2005-2010	R&D, demonstrations for different applications	Depending of applica-tions: thousands – hundreds of thousands
Grid connection for distributed energy production	2005-2010	R&D, demonstrations for different capacity classes	Depending of applica-tions: thousands – hundreds of thousands
Residential heating and refined fuels	R&D needs	**R&D need and demonstration investments**	**Business volume in Finland and in other countries by 2010**
Fire places	Emissions, efficiency, O&M	Development of new products	FIN: thousands Europe: tens of thousands
Automatic heating systems	Emissions, efficiency, O&M	Development of new products	FIN: thousands Europe: tens of thousands
Production of pellets and other densified products	Quality, raw material, drying, energy con-sumption	Demonstration at 1–3 factories, 2–3.5 M€/factory	FIN: tens of factories Europe: hundreds of factories

… Table 5. continues

Technology, Power-to-heat ratio	Year of commercial implementation	R&D need and demonstration investments	Business volume in Finland and in other countries by 2010
Production of pyrolysis oil	Production process, quality, distribution, storaging	R&D, 1–3 demonstrations at 1–3 factories, 8.5 M€/20 MW	FIN: 0.6 Mtoe in 10 plants Europe: tens of plants
Production of biofuels, especially using residues of the forest industry	Production process, quality, distribution, storaging	R&D, demonstrations	FIN: several plants Europe: tens of plants
Production and harvesting technologies of biomass-based fuels	R&D needs	**R&D need and demonstration investments**	**Business volume in Finland and in other countries by 2010**
Forest chips from regeneration fellings	Optimisation of production chains, quality, storaging	Development of equipment and chains, 0.3–0.5 M€/chain	FIN: tens of chains Europe: several hundreds of chains
Forest chips from young stands	Development of simple equipment, optimisation of production chains	Development of equipment and chains, 0.1–0.3 M€/chain	FIN: 100 Europe: several hundreds of chains
Chips and logs for residential heating	Quality, storaging, distribution	Development of equipment and chains, 0.02–0.08 M€/chain	FIN: hundreds of chains Europe: thousands of chains
Agrobiomass	Harvesting, intgration to fibre production or to water purification	Development of equipment and chains, 0.2–0.35 M€/chain	FIN: tens of chains Europe: thousands of chains
Residues from industry	Quality improvement by drying, production biofuels and pellets	Development of equipment 0.02–3.4 M€	FIN: tens of chains Europe: several hundreds of chains

Publications and reports made under the project

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Distributed Energy Production: Technology, Fuels, Markets, CO_2 Emissions

Hajautettu energiantuotanto: teknologiat, polttoaineet, markkinat ja CO_2-päästöt

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Abstract

In this paper, distributed energy production (DEP) technologies, fuels, market potential, and the possibilities for the reduction of the CO_2 emissions have been studied. Here, energy production from renewable energy sources (RES) or small-scale combined heat and power (CHP) with a nominal power of less than 10 MW is defined as DEP. Of the RES for distributed electricity generation, hydro power and, in the near future, wind power are the most competitive in Finland. However, the growth of hydro and wind power is restricted by water conservation and land use legislation. In distributed heat production, biomass is already used widely in Finland. Of the CHP technologies, gas and diesel engines are the most competitive at the moment. The growth of all CHP technologies is restricted by the availability and price of the fuel. In Finland, CHP systems based on biomass fuels will become significant in the future.

In the market scenarios presented in this report, biomass boilers have the largest potential in Finland in the near future. In the long term, wind power also has a great potential. In the scenario based on the Finnish Action Plan for Renewable Energy Sources (APRES) and moderate development of small-scale CHP, hydro power is also significant. In the long term, solar energy and heat pumps will also become significant. Of the CHP technologies, the systems of the 1–10 MW scale have the greatest potential at the moment. In the long term, the smaller CHP systems will also become significant.

The potential of DEP for CO_2 emission reductions has been calculated based on the estimated market potentials. The aggregate CO_2 emission reduction potential of all DEP technologies (compared with the emissions of the year 2000 in Finland) is 0.5–1.2 Mt in 2010 with the current growth scenario, depending on whether the distributed electricity generation replaces the current average electricity generation or coal condensate power. In the APRES and moderate development of small-scale CHP scenario, the reduction potential would be 1.2–3.8 Mt in 2010. Compared with the current CO_2 emissions from the use of fossil fuels and peat (58 Mt, on the average during 1996–2000) and the Kyoto target of reducing the emissions to the 1990 level (54 Mt), distributed energy production can significantly further the realisation of this target.

Lyhennelmä

Tässä raportissa on esitetty hajautetun energiantuotannon teknologiat, polttoaineet, markkinapotentiaali sekä mahdollisuudet CO_2-päästöjen vähentämiseen. Hajautetuksi tuotannoksi on tässä katsottu nimellisteholtaan alle 10 MW:n uusiutuviin energialähteisiin tai yhdistettyyn sähkön ja lämmön tuotantoon (CHP) perustuva tuotanto. Sähköntuotantoon käytettävistä uusiutuvista energialähteistä kilpailukykyisimpiä ovat tällä hetkellä vesivoima ja lähitulevaisuudessa myös tuulivoima. Niiden kasvua rajoittavat kuitenkin vesistönsuojelu- ja maankäyttörajoitukset. Lämmöntuotannossa biomassaa käytetään jo nykyisin Suomessa merkittävästi. CHP-teknologioista tällä hetkellä kilpailukykyisimpiä ovat kaasu- ja dieselmoottorit. Kaikkien CHP-teknologioiden kasvukehitystä rajoittaa polttoaineen saatavuus ja hinta. Suomen oloissa merkittäväksi nousevat tulevaisuudessa biomassapohjaiset CHP-ratkaisut.

Tarkastelluissa markkinaskenaarioissa suurin potentiaali Suomessa on biomassakattiloilla, pitkällä tähtäimellä myös tuulivoimalla. KTM:n Uusiutuvien energialähteiden edistämisohjelmaan sekä pienimuotoisen CHP:n kohtuulliseen kehitykseen

perustuvassa skenaariossa myös pien- ja minivesivoima tulee merkittäväksi, pitkällä tähtäimellä myös aurinkoenergia ja lämpöpumput. CHP-teknologioista suurin markkinapotentiaali on kokoluokan 1–10 MW ratkaisuilla. Pitkällä tähtäimella alle 1 MW:n CHP-teknologioidenkin potentiaalin arvioidaan kasvavan.

Tässä raportissa arvioitujen markkinapotentiaalien perusteella on laskettu hajautetulla energiantuotannolla saavutettavissa oleva CO_2-päästövähennys Suomessa. Kaikkien teknologioiden avulla saavutettava yhteenlaskettu päästövähennys vuoteen 2000 verrattuna olisi hajautetun energiantuotannon kohtuulliseen kehitykseen perustuvassa skenaariossa 1,2–3,8 Mt vuonna 2010, riippuen siitä korvataanko hajautetulla sähkön-tuotannolla nykyistä keskimääräistä sähköntuotantoa vai hiililauhdetta. Verrattuna nykyisiin fossiilisten polttoaineiden ja turpeen energiankäytön aiheuttamiin CO_2-päästöihin (keskimäärin 58 Mt vuosina 1996–2000) ja Kioton sopimuksen mukaiseen tavoitteeseen palauttaa Suomen päästöt vuoden 1990 tasolle (54 Mt), voidaan hajautetulla energiantuotannolla edistää merkittävästi tämän tavoitteen toteutumista.

1 Introduction

Distributed energy production (DEP) is a fast-growing sector of energy technology. In this paper, the DEP technologies, fuels, market potential, and possibilities to reduce CO_2 emissions are studied. The study is a part of the Finnish Technology and Climate Change Programme (Climtech) and has been funded by the Finnish Technology Agency (Tekes), Gaia Group Oy, Finnish Energy Industries Federation (Finergy), Finnish Natural Gas Association, Technology Centre Oy Merinova Ab, Sermet Oy (Wärtsilä), and Waterpumps WP Oy.

In this study, energy production from renewable energy sources (RES) or small-scale combined heat and power (CHP) with a nominal power of less than 10 MW is defined as DEP. Furthermore, wind parks with a total capacity of more than 10 MW are included in this study. Note that the possible effects of different DEP technologies on each other are not taken into account.

The study is based on a thorough literature review and expert interviews. The main references have been the European Commission White Paper (EC 1997), IEA World Energy Outlook (IEA 2000), and Finnish Ministry of Trade and Industry Action Plan for Renewable Energy Sources and its background report (Helynen et al. 1999).

The study is divided into three parts: survey of DEP technologies and fuels (section 2), assessment of market potential (section 3) and potential for CO_2 emission reductions in Finland (section 4). The following renewable energy sources and small-scale CHP technologies are included in the study:

Renewable energy sources:
- wind power
- hydro power
- solar energy (photovoltaics and solar thermal)
- heat pumps
- biomass boilers.

Small-scale CHP:
- gas and diesel engines
- microturbines
- stirling engines
- fuel cells
- steam turbines and engines.

2 Distributed energy technologies and fuels

The main performance and economic parameters of each distributed energy production technology are summarised in Table 1. Of the renewable energy sources for distributed electricity generation, hydro power and, in the near future, wind power are the most competitive in Finland. Especially, hydro power is competitive in sites where the utilisation time is over 4000 h. Wind power production cost is expected to drop down to 3 c/kWh in 5–10 years. However, the growth of hydro and wind power is restricted by water conservation and land use legislation. At the moment, photovoltaics (PV) is competitive only in special remote applications, but the price of PV is expected to go down in the long term. The technological potential of both PV and wind power is huge.

Table 1. Summary of renewable energy sources and small-scale CHP technologies.

	Unit power (kW)[1]	Electric efficiency (%)	Thermal efficiency (%)	Life time (a)[2]	Utilisation time (h)[3]	Investment cost (euro/kW)[4]	Production cost (c/kWh)[5]
Wind power	0.1–2500	40–50	–	20	2500	900–1100	4–5
Hydro power	20–10000	80–85	–	30	4000	1200–2000	2.5–4
Photovoltaics	0.004–0.1	4–12	–	25	1000	6500–10000	45–70
Solar thermal	0.3–0.8	–	30–40	20	1000	800–1600	7–14
Heat pumps	4–45	–	60–75	20	3000	900–1800	4–8
Biomass boilers	10–10000	–	70–90	20	1000/3500	100–200	1–5
Diesel and gas engines	3–10000	30–45	45–50	15	5000	450–1400	2.5–4
Microturbines	25–250	15–35	50–60	15	5000	1000–1700	3–4
Stirling engines	0.5–25	15–35	50–60	15	5000	1400–2200	4–5
Fuel cells	0.5–2000	38–55	30–45	15	5000	2800–4400	5–8
Steam engines and turbines	0.5–10000	15–35	40–70	15	5000	1500–3000	3–4

[1] Unit power is given as electric power, except for solar thermal, heat pumps, and biomass boilers as thermal power. The unit power can exceed 10 MW in some technologies, but this report includes only distributed energy production below 10 MW. Wind parks with total capacity over 10 MW are included.

[2] Lifetime varies in practice by plant. The value given here is used for the production cost calculation.

[3] Utilisation time varies in practice by year, by plant, and by site. The value given here is used for the calculation of the production cost and the CO_2 emission reduction potential (section 4). The utilisation time for biomass boilers is 1000 h in small combustion and 3500 h in district heating.

[4] Investment cost is given per electric power, except for solar thermal, heat pumps, and biomass boilers per thermal power. For CHP technologies, the investment cost is per electric power, but the given cost also includes the components related to the heat production.

[5] Production cost is given per produced energy unit including both electricity and heat for CHP technologies. For heat pumps, the production cost is given per net heat. The production cost is given without any tax reductions or investment subsidies. The production cost is calculated by discounting the investment cost over the lifetime of the power plant with the annuity method and 5% interest rate. The average 2001 wholesale price of natural gas in Finland (1.7 c/kWh) has been used as the fuel cost for the CHP technologies. For the CHP technologies, the power/heat ratio of 0.8 has been used for diesel and gas engines, 0.6 for microturbines and stirling engines, 1.0 for fuel cells, 0.6 for steam turbines, and 0.2 for steam engines. As there are many uncertainties regarding e.g. the lifetime, utilisation time, power/heat ratio, investment cost, and fuel price fluctuations, the estimates presented here only show the order of magnitude of the costs.

In distributed heat production, biomass is already competitive and is widely used in Finland. The potential of biomass utilisation is mainly restricted by the availability of fuel at a competitive price. Solar heating and heat pumps are not yet competitive with biomass, but their potential is also great. The use of solar energy is restricted by the long winter in Finland.

Of the CHP technologies, gas and diesel engines are the most competitive at the moment. Moreover, microturbines are feasible in small (below 100 kW) scale CHP. Fuel cells are expected to be significant in the long term, as their price is assumed to be reduced with mass production. The growth of all CHP technologies is restricted by the availability and price of the fuel. In Finland, CHP systems based on biomass fuels will be significant in the future.

The feasibility of various fuels for different CHP technologies is evaluated in Table 2. The evaluation is based mainly on the technological feasibility. All fuels are feasible for Stirling engines and steam engines and turbines, but most of them are not used in commercial CHP plants. Fuel cells have few commercial applications at the monment, most of them use hydrogen which is reformed from natural gas or methanol. The most important fuel for gas engines and microturbines is natural gas, diesel engines use diesel oil. Biomass or waste gasification is also a promising future solution, especially for gas engines in Finland.

Table 2. Feasibility of various fuels for different small-scale CHP technologies.

	Diesel and gas engines	**Micro-turbines**	**Stirling engines**	**Fuel cells**	**Steam engines and turbines**
Coal			•		• • •
Peat			•		• • •
Waste fuels	• •(gasified)	• •(gasified)	•	•(gasified)	• • •
Solid biomass	• •(gasified)	• •(gasified)	• •	•(gasified)	• • •
Diesel oil	• • •	• • •	• •		•
Gasoline	•	• •	• •	• •	•
Heavy fuel oil	• • •	•	•		•
Orimulsion	• •	•	•		•
Methanol	•	• •	• •	• •	•
Ethanol	•	• •	• •	• •	•
Bio oils	• •	• •	• •		•
LPG	• •	• • •	• •	• •	•
Hydrogen	• •	• •	• •	• • •	•
Natural gas	• • •	• • •	• • •	• • •	•
Bio gases	• • •	• •	• •	• •	•

• • • = commercially significant fuel at the moment
• • = possibly commercially significant fuel in the future
• = technologically feasible but probably not commercially significant fuel

3 Market potential of distributed energy technologies

In the market survey of this study, the technological, economical, and market potential of each technology has been assessed in the short (to 2005), the middle (2005–2010), and the long term (2010–2020). The potential of the different CHP technologies is assessed as a whole. Economical potential is defined as the part of the technologically feasible potential that is profitable to be carried out. Market potential is the part of the technological and economical potential that can be reached in each market situation. The market potential of each technology in Finland is assessed in three scenarios. Scenario 1 corresponds to the current market growth of each technology. Scenario 2 is based on the Action Plan for Renewable Energy Sources (APRES, by the Finnish Ministry of Trade and Industry) and moderate growth of the CHP technologies. Scenario 3 is equal to the economical potential for each technology.

The cumulative market potentials for each distributed electricity production technology is presented in Figure 1, and for each heat production technology in Figure 2. Biomass boilers have the greatest potential in the short term, but wind power is the most significant technology in the long term. In scenarios 2 and 3, hydro power is already significant, in the long term, solar energy and heat pumps become also significant. Of the CHP technologies, 1–10 MW systems have the greatest potential at the moment. In the long term, the potential of smaller (< 1 MW) systems is expected to grow.

In the APRES scenario (2), it is possible to build 900 MW new electric power capacity and 1200 MW new heat power capacity by 2010. With these capacities installed in 2010, it is possible to produce 3.1 TWh more electricity and 3.5 TWh more heat than in 2000. By 2020, it would be possible to build 2900 MW new electric power capacity and 3100 MW new heat power capacity. With these capacities installed in 2020, it is possible to produce 9.1 TWh more electricity and 9.2 TWh more heat than in 2000.

The worldwide growth of energy production also creates export markets for the Finnish technologies and know-how. Of the distributed energy production technologies, the greatest growth is expected in wind power, solar energy, biomass, and small-scale CHP. In these technologies, wind power

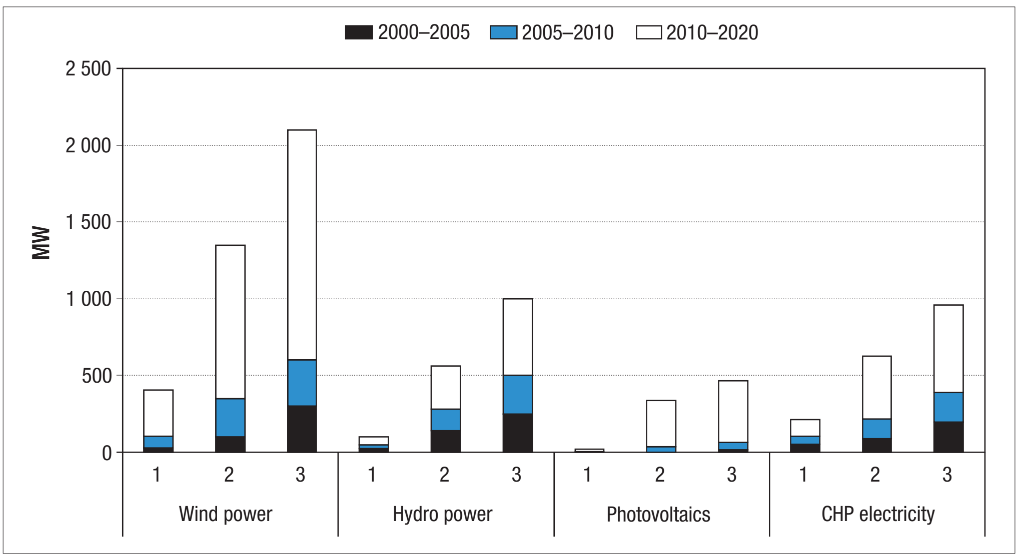

Figure 1. The cumulative market potential of distributed electricity production (< 10 MW) in Finland in scenarios 1, 2, and 3.

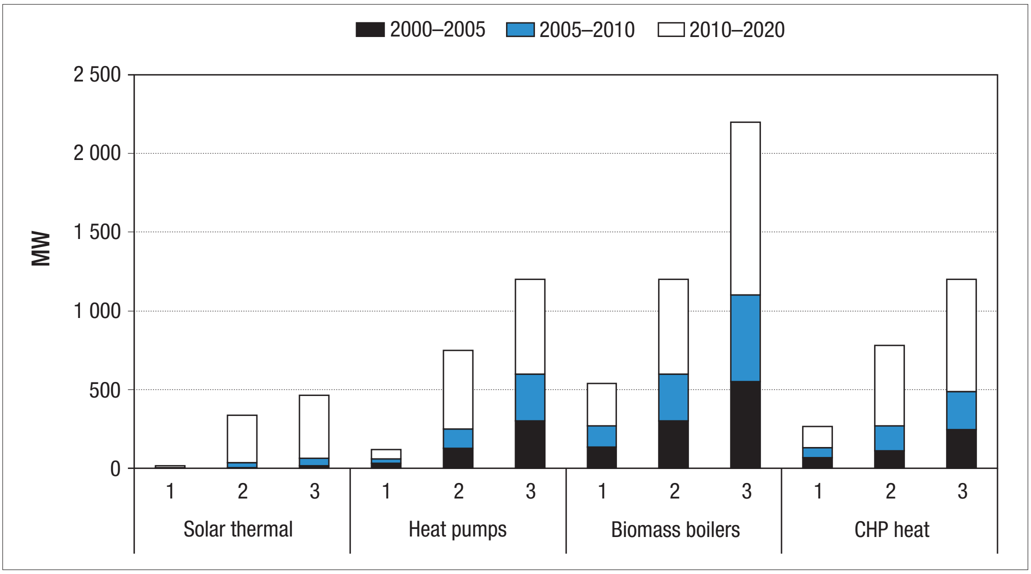

Figure 2. The cumulative market potential of distributed heat production (< 10 MW) in Finland in scenarios 1, 2, and 3. For CHP technologies, the power/heat ratio of 0.8 is assumed.

components, biomass fuels and combustion technologies, and gas engines are the strongest sectors in Finland. Moreover, hydro turbines/generators, and solar and fuel cell systems are potential export technologies. Distributed energy production will play an important role in the growth of the Finnish energy technology exports in the future.

4 CO_2 emission reduction potential in Finland

The potential of distributed energy production in reducing the CO_2 emissions (compared with the emissions in 2000 in Finland) has been calculated based on the market potentials estimated in this study. The CO_2 emission reduction potential has been calculated in two different comparisons: distributed electricity production replaces current average electricity production (200 kg CO_2/MWh) in comparison A and coal condensate power (850 kg CO_2/MWh) in comparison B. The distributed heat production replaces mainly light fuel oil (300 kg CO_2/MWh) in both comparisons. The comparisons A and B give the lower and upper limits for the CO_2 emission reduction potentials, the actual emission reductions will be between these limits. Note that the estimates in this report cannot be summed up with estimates presented in other reports, because the estimates in different reports might be overlapping.

The CO_2 emission reduction potentials in different scenarios in Finland in 2005, 2010, and 2020 (compared with the 2000 emissions) are presented in Figure 3 (with comparison A) and in Figure 4 (with comparison B).

In comparison A, especially wind power and solar energy are relatively less important than in the market scenarios, because these technologies have a lower utilisation time than the other technologies. Accordingly, CHP technologies are more important because they have a high utilisation time. Biomass boilers are also relatively important, because the light fuel oil replaced by the biomass has larger nominal CO_2 emissions than the average electricity production replaced by the other renewable energy sources.

In comparison B, biomass boilers are relatively less important than in comparison A, because their CO_2 emission reduction potential remains the same while the potential of the other renewable energy sources more than quadruples.

The aggregate cumulative market potentials, the additional electricity and heat production with these potentials, and CO_2 emission reduction potential of all distributed energy production technologies is presented in Table 3. Compared with the CO_2 emissions in 2000 in Finland, the reduction potential is 0.5–1.2 Mt in 2010 with the current growth scenario (1), depending on whether the distributed electricity generation replaces the current average electricity generation or coal condensate power. In the APRES and moderate development of small-scale CHP scenario (2), the reduction potential would be 1.2–3.8 Mt in 2010. Compared with the current CO_2 emissions from the use of fossil fuels and peat (58 Mt, on the average during 1996–2000) and the Kyoto target of reducing the emissions at the 1990 level (54 Mt) (Statistics Finland 2001), distributed energy production can significantly further the realisation of this target.

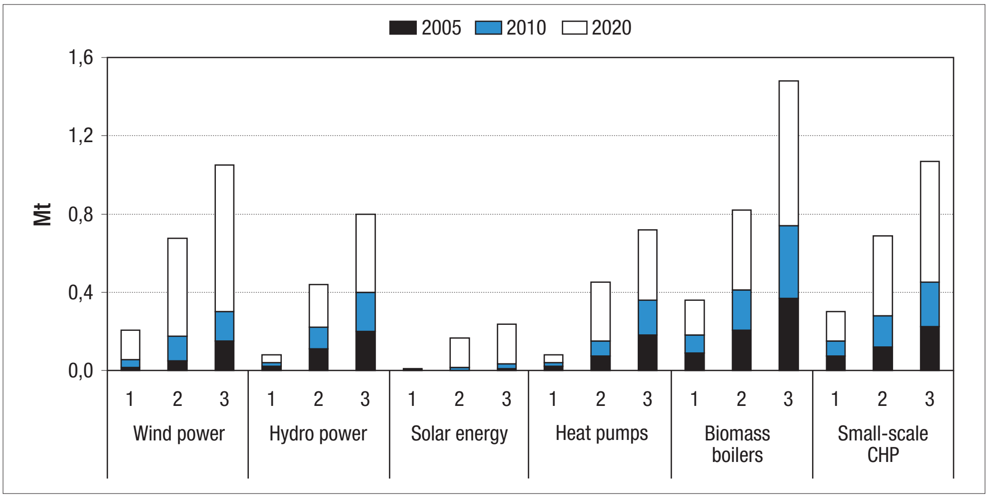

Figure 3. CO_2 emission reduction potential of distributed energy production (< 10 MW) in Finland (compared with emissions in 2000), comparison A (average electricity).

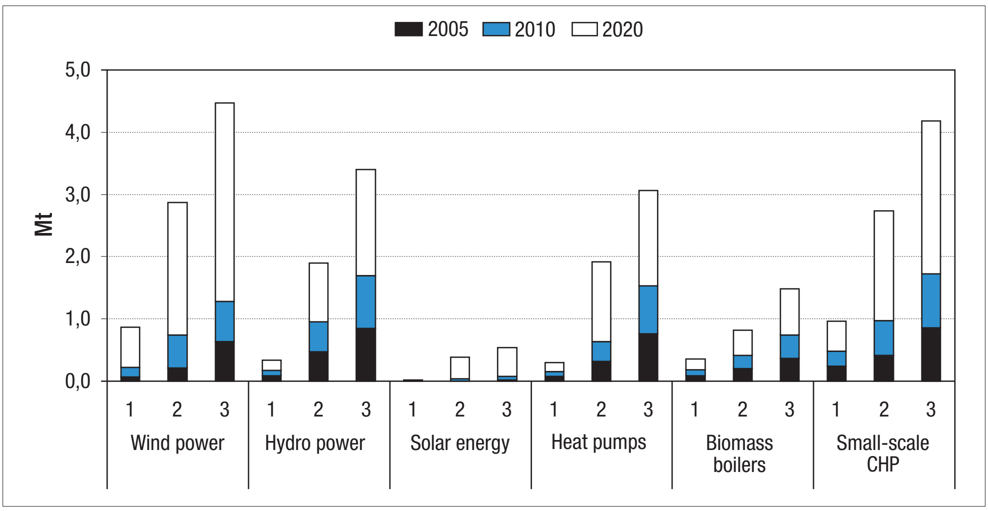

Figure 4. CO_2 emission reduction potential of distributed energy production (< 10 MW) in Finland (compared with emissions in 2000), comparison B (coal condensate power).

Table 3. The aggregate cumulative market potentials (MW), additional electricity and heat production with these potentials (TWh), and CO_2 emission reduction potentials (Mt) of all distributed energy production technologies in Finland (compared with 2000).

Cumulative market potential (compared with 2000), MW	Electric power			Thermal power		
	2005	2010	2020	2005	2010	2020
Scenario 1 (business as usual)	100	300	700	200	500	900
Scenario 2 (moderate growth)	300	900	2900	500	1200	3100
Scenario 3 (strong growth)	800	1600	4500	1100	2300	5100

Additional energy production (compared with 2000), TWh	Electricity			Heat		
	2005	2010	2020	2005	2010	2020
Scenario 1	0.4	1.0	2.4	0.7	1.5	2.9
Scenario 2	1.3	3.1	9.1	1.6	3.5	9.2
Scenario 3	2.7	5.5	14.5	3.4	6.8	15.0

CO_2 emissions (Mt) reduction potential (compared with 2000)	Comparison A			Comparison B		
	2005	2010	2020	2005	2010	2020
Scenario 1	0.2	0.5	1.0	0.6	1.2	2.9
Scenario 2	0.6	1.2	3.2	1.6	3.8	10.6
Scenario 3	1.1	2.3	5.4	3.5	7.0	(17.1)

Comparison A: distributed electricity production is assumed to replace average electricity production.

Comparison B: distributed electricity production is assumed to replace coal condensate power.
Note that there will not necessarily be enough coal condensate power in 2020 to be replaced in scenario 3.

5 Conclusions

Distributed energy production is a fast-growing sector of energy technology. In Finland, the most competitive technologies at the moment are biomass boilers, hydro and wind power, and gas and diesel engines. The growth of these technologies is mainly restricted by water conservation, land use legislation, and the price and availability of the fuels (natural gas and biomass). The most potential Finnish export technologies are wind power components, biomass fuels and combustion technologies, and gas engines. With a moderate growth of distributed energy production, the Finnish CO_2 emissions can be reduced by 1.2–3.8 Mt by 2010. However, this requires that the Finnish Action Plan for Renewable Energy Sources with the related support actions will be completed.

Publications and reports made under the project

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Future Possibilities of Hydrogen Technologies

Vetyteknologian kartoitus

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Abstract

The importance of hydrogen technologies were evaluated in the Tekes project "Road-Map for Hydrogen Technologies". The project has taken both the international and national development into account in order to find the most promising fields of hydrogen technologies for Finland

The use of hydrogen in the energy economy is quite low. Over 90% of the hydrogen consumption in the world is from the chemical industry. The hydrogen consumption is equivalent to about 100 Mtoe/a or slightly over 1% of the world's total energy consumption. The corresponding figure in Finland is about 2%. The main producers and users of hydrogen in Finland are Fortum Oyj and Kemira Oyj.

In an industrial sense, the hydrogen is a basic raw material for process and chemical industries and the related technology is well known. The main motive to the energy use of hydrogen is the connection to efficient end-use technologies, which enables better performance and smaller emissions. The fuel cells have been found to be the most interesting new hydrogen technology. The importance of peripheral technologies, such as hydrogen storage and small-scale H_2 production, is growing with the use of fuel cells. The market penetration of fuel cells requires great technological and financial efforts.

In order to be able to tailor together the schedule of market penetration and the critical factors of hydrogen energy in Finland, a few hydrogen scenarios were made. For example, the use of 1 Mtoe/a (3% from the whole primary energy) of hydrogen energy in the transportation sector would demand approximately 50 000 MW of fuel cells, which is over 1 000 times EU's fuel cell capacity estimated in 2010. The price of fuel cells would have to fall to one twentieth of the present price in order to enable such large-scale use. This could be possible somewhere between 2025–2030.

The scenarios brought up some critical peripheral technologies. Small-scale gasification and processing of solid biomass, hydrogen storage, small on-board stores, and pressurized electrolysis equipment are some of the most interesting technologies.

Tiivistelmä

Tekesin ClimTech-ohjelman projektissa "vetyteknologian kartoitus" on arvioitu vetyteknologian merkitystä keskipitkällä aikatähtäimellä. Selvityksessä on paikannettu alan kehityskohteita ja Suomelle kiinnostavia osa-alueita niin kansainvälisen kehityksen valossa kuin myös kotimaiset lähtökohdat huomioon ottaen.

Vedyn käyttö energiataloudessa on hyvin vähäistä. Yli 90 % kaikesta vedystä maailmassa käytetään kemian teollisuudessa. Energiaksi muutettuna vedyn käyttö vastaa noin 100 Mtoe/v tai runsas 1 % koko maailman energian kulutuksesta. Suomessa käytetty vety vastaa noin 2 % koko maan energiantuotannosta. Suomessa vedyn suurtuottajia ja -käyttäjiä ovat olleet Fortum Oy ja Kemira Oy.

Teollisessa mielessä vety on prosessi- ja kemianteollisuuden perusraaka-aine ja tähän liittyvä tekniikka on hyvin tunnettua. Pääasiallinen motiivi vedyn energiankäytölle löytyy sen yhdistämisestä tehokkaaseen loppukäyttöteknologiaan, jolloin saadaan parempi ominaissuoritetaso ja pienemmät päästöt. Esimerkiksi maakaasusta valmistettu H_2 polttokennoautossa pienentää kasvihuonekaasupäästöjä 60–80 % bensiinikäyttöiseen autoon verrattuna. Selvityksessä onkin paikannettu poltto-

kennot tärkeimmäksi uudeksi vetyteknologian alueeksi, jonka pääasialliset markkinasegmentit ovat liikenne, stationaariset pienvoimalat sekä kannettavat sovellukset. Polttokennojen kautta oheisteknologioiden, kuten vedyn varastoinnin ja pientuotannon, merkitys kasvavat. Polttokennojen kaupallistaminen ja saaminen markkinoille edellyttävät suuria kehitys- ja teknologiapanoksia.

Selvityksessä laadittiin muutamia vetyskenaarioita, joiden avulla pyrittiin hahmottamaan vetyenergian markkinoilletulon aikataulua Suomessa, mutta myös kriittiset pullonkaulateknologiat. Esimerkiksi 1 Mtoe/v vetyenergian käyttö liikenteessä polttokennoautoissa (3 % koko primäärienergiasta) edellyttäisi noin 50 000 MW:n verran polttokennoja, joka on yli tuhatkertainen EU:n arvioituun polttokennokapasiteettiin verrattuna vuonna 2010. Polttokennon hinnan tulisi pudota kahdeskymmenesosaan nykyisestä, jotta laaja käyttö olisi mahdollista. Tämä voisi toteutua arviolta 2025– 2030.

Skenaarioanalyysit nostavat esille eräitä kriittisiä oheisteknologioita. Pienen mittakaavan kiinteän biomassan kaasutus ja prosessointi, vedyn varastointi, pienet on-board-tyyppiset varastot ja näihin liitettävät pienemmät paineistetut elektrolyysilaitteistot ovat kiinnostavia kehityskohteita.

1 Introduction

Hydrogen is a clean fuel whose energy density is 33 kWh/kg or 3 kWh/m^3. Conversion of hydrogen into end-use energy (electricity, heat) produces mainly water vapor (H_2O). The production of hydrogen may produce some carbon dioxide.

Hydrogen is an energy carrier, not an energy source. It can be produced from primary energy sources and hydrocarbons (C_nH_m). Usually hydrogen is produced by steam reforming of natural gas ($CH_4+2H_2O \rightarrow 4H_2+CO_2$), or in smaller amounts by electrolysis of water ($2H_2O$+electiricity$\rightarrow$ $2H_2+O_2$).

Over 90% of the world's hydrogen is consumed in the production of fertilizers and by the petrochemical industry (e.g. in cracking). Other industrial uses of hydrogen are for example in production of fats and semiconductors. The major energy use of hydrogen is its use as a rocket propellant. The total consumption of hydrogen is equivalent to about 100 Mtoe/a or slightly over 1% of the world's total energy consumption. The price and markets of H_2 are largely dependent on its need in industrial processes and on the raw material used in the production. The H_2 consumption in Finland is equivalent of about 2% of the whole energy consumption in the country.

The use of H_2 energy is always more expensive than the primary energy itself. The H_2 energy produced from natural gas is 2–3 times more expensive than natural gas, and H_2 energy produced by gasification of biomass is 4–5 times more expensive than the biomass itself. H_2 made by electrolysis is 2–4 times more expensive than electricity.

The main motive to the energy use of H_2 is the connection to efficient end-use technologies. The emission problems of transportation and the development of H_2-using fuel cells enhance the interest towards H_2. For example, the use of H_2 that is reformed from natural gas in a fuel cell car diminishes the emissions of greenhouse gases 60–80% compared to a gasoline-fueled car.

In an industrial sense, the H_2 is basic raw material in process and chemical industries, and the related technology is well known. Fuel cell technology is the most interesting new H_2 technology. The importance of peripheral technologies, such as H_2 storage and small-scale production, is growing with the use of fuel cells. The market penetration of fuel cells requires great technological and financial efforts.

Some long-term energy scenarios view H_2 as the basis of a sustainable energy development in 2050–2100. It is estimated that on a medium-term time scale the H_2 production potential is about 6 TWh_{th}/a in the Nordic Countries. On a very long-term time scale, this potential will rise to over 200 TWh_{th}/a, and main energy sources would be natural gas and renewable energy sources.

2 Storage of Hydrogen

2.1 Hydrogen Storage Technologies

Hydrogen is a difficult element to store because it is a small molecule gas. Even though hydrogen has a very good gravimetric energy density, its gaseous form causes that even a small amount of it needs a large volume or a very large pressure. For transportation application hydrogen also needs a proper distribution infrastructure.

The present state and future potential of hydrogen storage technologies were evaluated within the project (Hottinen 2001). The hydrogen storage capacities of different storage technologies are given in Table 1 below. Also, the possible application areas of different technologies are given (transp = transportation, CHP = combined heat and power production, port = portable electronics).

Only a few of storage technologies are suitable for real applications. Gaseous hydrogen is suitable for large and medium-scale applications, in which it is easy and safe to use elevated pressures. Gaseous hydrogen is probably not suitable for portable electronics, since it would demand large pressure regulators and causes a possible safety risk. The use of new composite containers is more expensive than the traditional steel and aluminum bottles, but the energy density is much higher. A composite container storage costs about 7 €/kWh (the cost of storage per storing capacity).

Because of the large volume needed, the gaseous hydrogen containers are suitable for applications in which the need of energy is at maximum about 500 kg of H_2, i.e. approximately 4 GWh (200 bar). Hydrogen can also be stored in subsurface caves and caverns. This kind of cave can have even a volume of 100 000 m^3 and a pressure of hydrogen about 100 bar, so a subsurface cave may be able to store as much as 30 GWh of energy. One of the main problems of subsurface storage methods is the leakage loss. This kind of cave storage has not been implemented in practice yet.

The liquefaction of hydrogen consumes lots of energy (about one third of hydrogen energy content), and is thus quite expensive storage method to use. This is why it is most suitable for applications in which the size and mass of the storage is critical and the cost is not. The cost of liquid hydrogen storage is about 7 €/kWh, which is increased with usually quite large boil-off losses. Liquid hydrogen is mainly used as rocket propellant storage method (NASA). The biggest separate liquid hydrogen tanks can be about 4 000 m^3 in size (appr. 10 GWh). Some fuel cell car developers have designed a liq-

Table 1. The storage capacities of different hydrogen storage technologies.

Storage method	Hydrogen capacity	Energy capacity	Applications
Gaseous H_2	11.3 m-%	5.0 kWh/kg	transp, CHP
Liquid H_2	25.9 m-%	13.8 kWh/kg	transp
Metal hybride	~2–5.5 m-%	0.8–2.3 kWh/kg	port, transp
Activated carbon	5.2 m-%	2.2 kWh/kg	–
Zeolites	0.8 m-%	0.3 kWh/kg	–
Glass spheres	6 m-%	2.5 kWh/kg	–
Nanotubes	4.2–7 m-%	1.7–3.0 kWh/kg	port, transp
Fullerens	~6 m-%	2.5 kWh/kg	port, transp
Chemical	8.9–15.1 m-%	3.8–7.0 kWh/kg	all

uid hydrogen tank into their fuel cell car (BMW, Mercedes-Benz). The size of liquid hydrogen tank in transportation applications is in the scale of 120 l (appr. 300 kWh).

Metal hydrides have quite a poor storage capacity compared to gaseous and liquid hydrogen. However, the metal hydrides are quite small. At best they can store even more energy in the same volume than liquid hydrogen. Excellent pressure-temperature properties for practical applications can be achieved with proper kinds of metal hydrides, enabling the use of small pressure regulators. Because of these properties, the metal hydrides are suitable only for small and medium-scale applications, such as portable electronics and possibly transportation. The cost of metal hydride storage is dozens of €/kWh because of several difficult manufacturing phases.

Figure 1. 20 l of hydrogen storing metal hydride container and a normal D-type battery.

An example of a small metal hydride container is illustrated in Figure 1. The container can store 20 Nl of hydrogen corresponding the energy content of about 78 Wh. A normal D-type battery (1.5 Wh) is also in the figure for size comparison.

The nanostructures of carbon, especially nanotubes, are maybe the most promising hydrogen storage method of the future. Good hydrogen storage capacities with nanotubes have been achieved in laboratory conditions. Real nanotube storage has not been demonstrated yet, and thus they have lots of open questions to be solved. The price of nanotubes is still tremendously high (appr. 100 €/g corresponding almost 60 000 €/kWh).

Table 2. Energy densities of some typical synthetic fuels.

Fuel	Energy density	
	kJ/kg	MJ/m^3
Gasoline	43000	37000
Gaseous H_2	120000	10
Liquid H_2	120000	8700
Methanol	20000	16000
Ethanol	27000	21000
Natural gas	46000	33
Ammonia	17000	13

Hydrogen can also be stored indirectly in the form of synthetic fuels. Energy densities of some typical synthetic fuels have been gathered in Table 2.

2.2 International and National Actors

The research of hydrogen storage technologies is nowadays mainly concentrated on manufacturing techniques and material development. New composite containers for gaseous hydrogen storage have been researched and developed mainly by Quantum Technologies, Inc. from Canada. The biggest names in the field of liquid hydrogen storage are e.g. Linde AG and L'Air Liquide.

The metal hydride research around the world is concentrated on finding metal compounds that are easier to manufacture and have better hydrogen storage properties. One of the biggest international manufacturers of metal hydrides is Gfe mbH from Germany. Hydrogen storage in carbon nanostructures is being actively studied in several research institutes around the world.

The basic know-how in the field of chemical compounds is on solid ground especially in the chemical industry. The storage of chemical compounds is well known, and is thus not a challenge. The main problems are the fuel processing for the end-user and possible influences on health.

There is a lot of domestic know-how in the field of synthetic fuels. The gasification of biomass and the production of synthetic fuels from biomass (such as peat) are actively studied. One of the largest actors in the field is Kemira Oy, which has experience over a long time especially in the manufacturing of ammonia.

The compounds needed in metal hydrides are manufactured by Outokumpu Oy. The research in the field is mainly carried out at HUT and VTT. HUT has concentrated mainly on the properties of low temperature and pressure metal hydrides, and VTT mainly on metal hydride applications.

3 Fuel Cells

3.1 Fuel Cell Technologies

Fuel cells are electrochemical devices that convert the chemical energy of hydrogen directly into electricity and heat with water being the only reaction product. Fuel cell reaction is purely electrochemical, and thus there is no burning with flame as in internal combustion devices. The main fuel cell reaction is (e.g. in PEM fuel cell):

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + electricity + heat.$$

The operation principle of fuel cell is illustrated in Figure 2.

In small power scale fuel cells may replace battery technology in portable electronics. In medium power scale fuel cells can operate as power supply for vehicles instead of combustion engines or e.g. in small-scale combined heat and power production (µCHP). The large-scale applications are in power production.

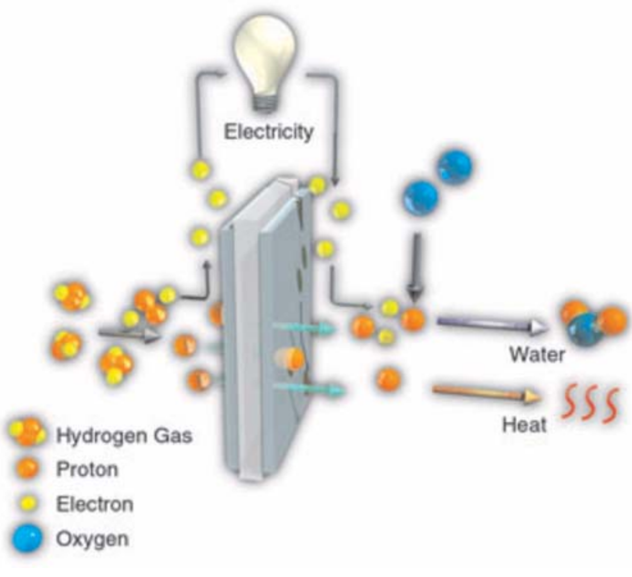

Figure 2. Operation principle of PEM fuel cell (image: Plug Power)

Some properties of different types of fuel cells and future potential (– no potential, + some potential, ++ very good potential) are summarized in Table 3.

Table 3. Properties of different types of fuel cells.

Type of fuel cell	PEMFC	AFC	PAFC	MCFC	SOFC
electrolyte	polymer membrane	alkaline	phosphoric acid	molten carbonate	ceramic zirconium-oxide
temperature	40–90 °C	65–200 °C	170–200 °C	600–800 °C	600–1100 °C
fuel	H_2	H_2	H_2	H_2, reforming of hydrocarbons	H_2, reforming of hydrocarbons
el. efficiency	35–40%	40–50%	40–50%	50–60%	45–55%
power scale	< 1W–500 kW	10–100 kW	< 10 MW	< 100 MW	< 100 MW
applications	port., trans., µCHP	transportation, µHCP	CHP	CHP	CHP
future potential	++	–	–	+	++

3.2 International Interest in Fuel Cells

There are great efforts on the development and marketing of fuel cells throughout the world, especially in automotive industry. Almost all of the car manufacturers are developing a PEM fuel cell car of their own. For example, Toyota and Daimler-Chrysler have announced that they will bring their fuel cell cars to market within two years.

In CHP-applications ALSTOM's 200 kW PEMFC plant, FCE-MTU's MCFC plant, and Siemens-Westinghouse's SOFC plant are on their way to market. IFC-ONSI's PAFC plant has already been on the market for a while. Siemens- Westinghouse is also bringing to market a combi plant in which a gas turbine is attached to a SOFC. Several energy companies have shown interest in fuel cell power production.

The suggested less than 10 kW µCHP residential applications are mainly based on PEMFC (Vaillant, H-Power), but SOFC-based solutions are also being developed (Sulzer-Hexis). Solutions for other medium-scale applications, such as weather and link stations, are also on the market (NAPS, H-Power). The manufacturers of small-scale battery-using equipment, such as portable computers and mobile phones, are also active on developing fuel cells (Motorola, Nokia, ZSW, Casio).

3.3 Research and Interest on Fuel Cells in Finland

Fuel cells are studied in Finland at Universities (TKK, HY, ÅA) and Technical Research Centre of Finland (VTT), and also in some companies. Research is mainly concentrated on structural and material solutions, and on system development. NAPS Systems Oy has the only commercially available fuel cell based energy system product. In the system, the excess solar energy is used to produce hydrogen and when the solar energy is not enough to cover the need of the load, the fuel cell is used as a backup power system. Hydrocell Oy produces AFCs for small applications.

Wärtsilä Oy is going to develop a solid oxide fuel cell system, but most of the Finnish companies (NAPS, Tamrock, and some others) are more interested in developing their product on imported PEMFCs. Kemira produces catalysts that are used in the autoreforming of high-temperature fuel cells. Some interest has also been shown in the fuel cell structure related matters (Optatech). The Finnish fuel cell research is on very initial stage in international comparison.

4 Other Hydrogen Technologies

4.1 Hydrogen Production

The main part of hydrogen production is devoted to ammonia production in the fertilizer industry, and to crude oil cracking and desulphurization at oil refineries. There are also numerous other uses, including the production of industrial chemicals, applications in metal and electronics industries, and margarine hydration in food industry.

The principal production method of hydrogen is steam reforming, in which up to 89% of the energy content of natural gas is converted to the energy content of hydrogen. The amount of carbon dioxide released is proportional to the consumption of natural gas. The carbon dioxide emission resulting from natural gas production affects the figures significantly. According to an US study, only 64% of the energy content of a natural gas deposit can be converted to the energy of hydrogen, and this figure does not contain the conversion of released methane to equivalent carbon dioxide.

Water electrolysis in an alternative H_2 production method, but it currently accounts only for 1–4% of all H_2 production. Mainly in the production of hydrogen for special purposes, electrolysis is significantly used. Estimated hydrogen prices for different production methods and raw materials are presented in Table 4.

4.2 International Outlook on Hydrogen Technologies

The global hydrogen consumption is 390 000 Mm^3 per year, which equals to 100 Mtoe of energy. The world primary energy consumption is approx. 9 000 Mtoe, which means that the current hydrogen production could cover slightly more than one

Table 4. Hydrogen production prices (Koljonen et al. 2001, Gaudernack et al. 1994).

Size pf prod. site Mm^3 (n)/d MW	Raw material	Hydrogen price €/GJ
	Steam reforming	
0.27	natural gas (3 €/GJ)	11.2
6.75	natural gas (3 €/GJ)	5.4
25.4	natural gas (3 €/GJ)	6.0
	Gasification	
6.78	coal (1,5 €/GJ)	9.9
2.80	waste oil (1,4 €/GJ)	9.8
2.26	biomass (46,3 €/GJ, dry wood)	10
	Electrolysis	
0.247	water (windpower)	20
6.75	water (0,049 €/kWh, electricity)	25
0.63	water (0,0252 €/kWh, electricity)	17

percent of global energy requirements. However, the hydrogen production is mainly consumed in industrial processes, and the only significant energy use of hydrogen is currently as rocket fuel.

Hydrogen production from natural gas and the dumping of carbon dioxide into the gas field has been studied in Norway (Kvarner, Norsk Hydro). A fuel cell bus has been test driven in Oslo already in 1999 (Stor-Oslo Lokaltrafikk). In Iceland, large expansions of electrolytic hydrogen production capacity have been proposed, taking advantage of the availability of cheap hydro power. This could eventually lead to transition to a full hydrogen economy. In Denmark, Haldor/Topsoe is a leader of fuel processing.

4.3 Finnish Outlook on Hydrogen Technologies

The largest user of hydrogen in Finland is Fortum Oyj, with oil refineries in Porvoo and Naantali. The hydrogen consumption of Kemira in fertilizer production is not known. Small amounts for special applications are produced by Woikoski Oy and Aga Oy. Significant quantities of hydrogen are produced by Finnish Chemicals, as a by-product of chlorate production for the paper industry.

The main hydrogen production sites in Finland are listed in Table 5 and 6. Hydrogen has been produced in Finland by peat gasification (Kemira). Small electrolyzers are developed and produced by

Table 5. Hydrogen production sites in Finland in 1996 (Zittel 1997).

Production site	Amount Mm^3/a	Production method
Finnish Peroxides Oy, Voikkaa	18	steam reforming
Kymmene Corporation, Kuusankoski		steam reforming
Neste Oy, Porvoo	150 300	steam reforming as a by-product
Finnish Chemicals, Oy, Joutseno		chlorine electrolysis
Finnish Chemicals, Oy, Kuusankoski		chlorine electrolysis
Veitsiluoto Oy, Forest Chemical Industry, Oulu		chlorine electrolysis
Nokia, Äetsä		chlorine electrolysis
Nokia, Joutseno		chlorine electrolysis
Oulu Oy, Oulu		chlorine electrolysis
Outokumpu Harjavalta Metals Oy	16	steam reforming
Espoo, electronic companies etc.		small H_2 generators

Table 6. Estimates on hydrogen production in 2002.

Producer	Amount Mm^3/a
Fortum, Porvoo	1000
Fortum, Naantali	200
Aga Oy	22
Woikoski Oy	not available
Finnish Chemicals	120

LabGas Instrument Co. Metallic materials for hydrogen storage (metal hydrides) are produced (Outokumpu). Research on catalysts for fuel processing for fuel cells is done (Kemira Metalkat).

5 Scenarios

Hydrogen consumption in Finland equals to about 2% of total primary energy consumption. The hydrogen is mostly used in industrial processes. A large part of the total production is derived as a by-product of industrial processes. H_2 offers promising opportunities for the reduction of carbon dioxide emissions in transportation.

The efficiency of energy production is improved by up to a factor of three by transition from internal combustion engines to fuel cells. The total reduction of emissions is dependent on the hydrogen production method and the production efficiency. When hydrogen or methanol produced from fossil raw materials, or gasoline, is used as fuel in fuel cells in transportation, the improvement from the present situation is small, compared to completely carbon dioxide free raw materials.

The share of transportation in the total energy consumption in Finland is 17%, and the consumption consists currently mainly of oil (5 Mtoe). The use of bioenergy is 6.6 Mtoe, which is mainly due to the wood processing industry. The consumption of natural gas in Finland is 3.8 Mtoe (4100 Mm^3) per year. The annual carbon dioxide emission is 54 millions of tons. The total CO_2-emission from road traffic was 11 Gkg, from which 6 Gkg originated from private vehicles.

In Finland, 47.7 billion car-kilometers are driven each year. In Figure 3, the reductions of greenhouse gas emissions over the entire fuel chain are compared in three different cases, if 18.3 milliards of km (38%) are driven using alternative vehicles and fuels. The distance driven was chosen to correspond to 1 Mtoe of biomass. All of the vehicles are assumed to be family cars of equal weight and power (1300 kg, 50 kW). The base case is a gasoline-powered vehicle with consumption of 2.18 MJ/k m (n. 7 liters /100 km), CO_2 (equivalent) emissions 188 g/km, of which 163 g/km during actual driving.

The sources used in the following are (Ohlström et al. 2001, Spath & Mann 2001, Koljonen et al. 2001, Cuoco et al. 1995, Motiva). As for the emissions of

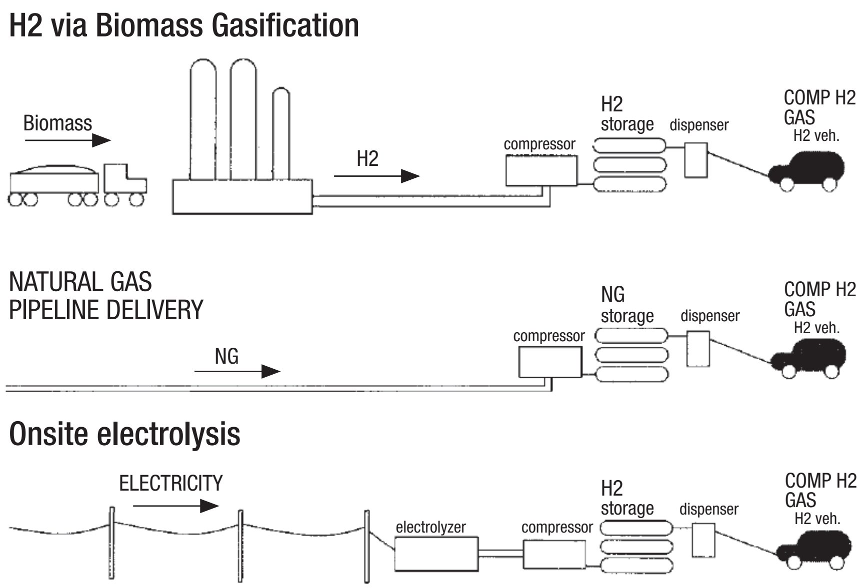

Figure 3. Fuel chains for three cases analysed. (mainly: Odgen et al. 1999)

natural gas production, a Finnish calculation method was chosen.

1) Biomass (wood chips)

It is assumed, that 1 Mtoe of biomass could be used annually in the Finnish transportation system. This amount of wood chips (52.26 millions of m^3 solid) equals to the current annual small-scale use in Finland, and it could be obtained from residuals of thinning and end harvesting. The conversion ratio from biomass to hydrogen is 60% (ΔG_{NTP}, dry H_2). The electricity needed for pressurization is produced on site from biomass, and this consumes 20% on the input energy. The annual hydrogen production is 170 000 tons (1900 Mm^3).

The consumption of a hydrogen-powered fuel cell car is assumed to be 1.1 MJ/km, and the CO_2 (equivalent) emission resulting from biomass collection etc. is assumed to be 3 g/km. The hydrogen production is sufficient for driving 18.3 milliards of kilometers. The reduction of CO_2 (equivalent) emissions compared to the base case is 185 g/km, or 3.4 Gkg.

2) Natural gas

Natural gas-powered vehicles account for 183 milliards of km (Otto engine, 1.86 MJ/km, 109 g CO_2/km, of which 94 g during actual driving). The electricity needed for gas compression (200 bar) is produced on site from natural gas (10% of energy). The consumption of natural gas is 0.9 Mtoe (970 Mm^3) and the CO_2 (equivalent) emission reduction is 79 g/km, or 1.4 Gkg.

3) Electrolysis

In this alternative, 18.3 milliards of kilometers are driven using hydrogen-powered fuel cell cars (1.1 MJ/km), for which the hydrogen is produced from water using electrolysis. The efficiency of electrolysis is assumed to be 70% (LHV), and 10% of the consumed electricity is needed for pressurization. The electricity consumption equals to 8.9 TWh, or the annual production of a 1100 MW power station. The CO_2-emission from nuclear power was assumed to be 15 g/kWh (7 g/km), mainly resulting from fuel production. The CO_2 emission for electricity produced from biomass was the same. The average figures for electricity production in Finland are 250 g/kWh (121 g/km). The CO_2-emission reduction using electricity from nuclear or biomass energy was thus 181 g/km, or 3.3 Gkg.

Bottlenecks

The maximum allowable distance for biomass transportation for gasification does not increase with increasing plant size. The size of a gasification plant is limited by this, and by the fact that the fuel distribution network must match the geographic patterns of consumption. Small-scale gasification plants are still at a development stage.

A large hydrogen tank is needed with a continuously operating electrolysis or gasification plant, whereas if the plant is connected to a natural gas line, a pressurized storage is not needed. The problems of pressurized hydrogen in light vehicles are not yet fully solved. High pressures are needed in order to reach an acceptable storage density.

In order to achieve a commercial break-through of hydrogen technologies, the development of fuel cell technology must proceed as anticipated. The use of hydrogen in internal combustion engines does not offer significant benefits compared to gasoline.

Comparison of alternatives and discussion

The planned driving distances (18.3 billions of kilometers) cover 45% of the Finnish light vehicle fleet, when the average annual driving distance is 19000 km. Other vehicle types account for 15–20% of the kilometers. The combined output power of the power sources of a million fuel cell cars is 50 000 MW. The serial production capacity needed for this will not be reality in very near future.

The technology needed for the natural gas alternative exists. In addition, when research on pressurized hydrogen technologies proceeds, better compressors and pressurized tanks will be available for use with natural gas also. The popularity of natural gas indicates that widespread use of gaseous fuels is a realistic vision. In Finland, the market penetration of natural gas vehicles is currently hindered by the additional tax imposed on them.

In Finland, wood chips (10 GJ/ton) cost 2.4 €/GJ, delivered to the power plant. If the allowed cost is increased to 3€/GJ, the available resources are

Table 7. Analyzed options compared to the use of gasoline.

	ΔE/km	ΔCO_2		Δ€/km
		Finland	Transportation	
Biomass-H_2	–2%	–6%	–31%	–13...+64%
Natural gas-CH_4	–12%	–3%	–13%	–7%
Electrolysis-H_2	–22% (η_e = 100%)	–6%	–30%	+9...+90%

doubled (Ylitalo 2000, Hakkila et al. 1996). Raw materials account for 10% of the cost of hydrogen produced from biomass. The investment cost of the equipment is the main cost component.

The delivery and distribution costs of pressurized hydrogen (20±10 €/GJ for H_2, LHV) must be added to the production cost (Padró & Putsche 1999, Cucco et al. 1995, Koljonen et al. 2001). There is large variation in the estimated costs.

The energy consumption of hydrogen production (Table 7.) has been assumed from the carbon dioxide emissions (not equivalent) on diesel oil basis (74 g ⇔ 1 MJ). Nuclear electricity is counted as primary energy. The comparison cost of gasoline without tax at the service station is 12.5 €/GJ (0.4 €/liter). The cost of electricity for electrolysis is 7 €/GJ (0.0252 €/kWh). Natural gas costs at service stations in Sweden 21 €/GJ, of which 7.4 €/GJ is tax. (Fordonsgas, DESS 2000).

6 Conclusions

From a market perspective, the principal applications of hydrogen and related technologies are in chemical and process industries, where substantial expertise of hydrogen production exists, especially from the point of view of hydrogen technologies. Hydrogen has no position in the energy economy, and on an energy basis, the production of hydrogen equals to slightly more than one percent of the Finnish and global energy use.

In this study, fuel cells have been identified as the most important new field of hydrogen technology. The principal market segments are transportation, small stationary power plants and CHP applications, and portable applications. Each of these includes significant peripheral technologies of hydrogen technology. The small applications probably represent a win-win -situation, whereas the others still contain significant risks.

Some hydrogen scenarios for Finland were developed. The use of 1 Mtoe equivalent of biomass annually in transportation, using fuel cell cars, corresponds to 170 000 tons/y hydrogen. This would require 50 000 MW of fuel cell vehicles or more than 1 000 times the assumed fuel cell capacity of EU in 2010. In this study, it was estimated that the scenario could become reality approximately in 2025–2030. A key prerequisite for this is sufficient development and market introduction of fuel cells. In practice, the cost of fuel cells should be decreased by a factor of 20 from the present level.

The scenarios highlighted a number of critical peripheral technologies. In biomass-based hydrogen production, small-scale gasification and processing of solid biomass is a central field of development. In electricity-based hydrogen production, hydrogen storage is an important topic. Because large-scale storage of hydrogen may not be feasible, this emphasizes the importance of small onboard type storage methods, and small, pressurized electrolyzers that could be connected to them.

The study indicates that hydrogen technology will have an impact on energy economy in 25–30 years at the earliest, and the investment needed in technology development and market introduction is significant.

Before large-scale applications, smaller niche-type hydrogen applications will become more widespread. Portable fuel cell applications are probably closest to this stage. The central technology fields will then be the small fuel cell, hydrogen storage and the auxiliary electronics. Another example is autonomous energy systems, in which the Finnish NAPS is an international market leader. In niche markets, the introduction of hydrogen energy is not driven by the price of hydrogen or energy.

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