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Towards zero emission energy production

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Zero emission energy production
– Wishful thinking or a dream come true

Ambitious targets have been drivers for many of mankind's scientific and technology breakthroughs. Unprejudiced ways to think and act have created radical new innovations, products and results. If we aim low, the results, of course, will be less. If we aim high, however, the results will be exceptional.

Sending a man to the moon was certainly just a dream, a "crazy idea" that many sceptics dismissed with smile, but that was before it happened in 1969. Who would have imagined that a project, utilising many different technologies, could result in finally putting a man on the moon? Getting there demanded ambitious targets, long-term commitments and strong will. A dream had become reality.

Achieving zero emission energy production will demand the same. But the challenges posed by energy production are very different from those posed by space travel. For one, energy is an everyday consumer necessity and a mandatory production enabler for industry.

Most energy has to be produced at the same time as it is consumed. Energy production has both local and global impacts, many of them long term and crucial to humanity's fate. Climate change is a concrete example of how local energy production can affect the global emission balance.

Global energy questions need global political decisions. Technology can provide solutions but implementing and regulating the use of energy demands political will and commitment. In the climate mitigation process, this political will is on trial.

VTT, Technical Research Centre of Finland as a technology front-runner, sees efficient energy technologies and energy innovations as prerequisites for energy emission reduction.

The world's current situation requires the energy sector to set ambitious emission goals for itself. Zero emission energy production should now be our ultimate objective.

The energy industry must adapt its business and investments according to current regulations and price development. On the other hand, most long-term operators must also try to evaluate and forecast as much as possible. They should know the direction the world is going, and consider everything from the energy supply situation and price development to new technologies and eventual changes in political and regulatory environments.

Zero emission energy production is indeed a great objective for those companies who want to build their long term strategies on a sustainable future. But the importance of environmental issues will only increase. In the future it is not only short-term competition but long-term survival that will influence companies' decision making and thinking. For industry, environmental issues are now a permanent item on the agenda. And because decision mechanisms and business cycles in the energy sector are very long, policy and industrial decision makers should rely more on research and development.

Momentum is here

The current economic recession, high energy prices and new energy saving technologies are helping consumers and society to reduce energy consumption. This means that the market for new energy technologies is growing fast.

It is evident that the market for bioenergy and technology for emission reduction as well as energy saving will be an extensive one.

This is an opportunity for Finland's technology industry, one that it shouldn't miss. Finland's technology industry, with its focus on energy-saving and emission reductions, is uniquely positioned to take advantage of this promising market outlook. This is also a potential benefit for the entire national economy of Finland.

The time to build the foundation for low emission energy production, energy savings and energy efficient technologies is now.

Zero emission energy production sets more than technological targets. It also creates intellectual and ethical ones. The combination of these make the R&D industry work harder. Research organisations cannot, however, work by themselves. They need political incentives, capital injections, industry investments and customers. At the moment, there are many good signs which show that zero emission energy production is becoming a real option: political will exists, industry is showing interest and R&D organisations are developing competent technologies.

On the basis of these signs, we can see real zero emission energy production becoming a reality – if not for us, then at least for the coming generations.

Olli Ernvall
VTT
Senior Vice President, Communications

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Ilkka Savolainen, Research Professor
Antti Lehtilä, Senior Research Scientist
Lassi Similä, Research Scientist

Abstract

If the global temperature rise is to be limited to 2°C compared with the pre-industrial temperature level, global greenhouse gas emissions will have to be reduced by 50–85 per cent from the current levels by 2050, according to the IPCC. Furthermore, the industrial countries will have to cut their emissions by 80–95% by 2050 and by 25–40% by 2020 to achieve this warming limit. The European Union has announced its readiness to cut emissions by 30 per cent from the 1990 level by 2020 if other industrialised countries also proceed with corresponding reductions. The EU has unilaterally undertaken a commitment to reduce emissions by 20 per cent by 2020, and has also proposed indicatively to cut its emissions by 60–80 per cent by 2050.

In Finland, greenhouse gas emissions can be reduced by 60–66% from 1990 to 2050 according to the scenario study presented in this article, if the emission rights price rises no higher than 80 €/tCO_2-eq. Increased energy efficiency becomes an important factor in emission reductions. The most important energy production technologies which reduce emissions are bioenergy technologies, wind power and nuclear power. There will be a strong decrease of greenhouse gas emissions in the sectors of condensing-based electricity production, district heating, and separate heating. Most of the emission reduction will take place in ETS rather than the non-ETS sector. It is very likely that the global and European emission reduction policies will also cause a rapid development of the markets for new energy technologies, which will create opportunities also for Finnish R&D and manufacturing companies.

1. Introduction

Anthropogenic climate change is a huge challenge to mankind. The global average temperature has already risen by 0.8 degrees Celsius from the pre-industrial temperature level some two hundred years ago. The warming rate is climbing due to the increased amount of accumulated greenhouse gases in the atmosphere. Without effective control of greenhouse gas emissions the global average temperature is expected to rise by 2100 a further 2 to 4 degrees, even 6 degrees if uncertainty as to the atmospheric response is taken into account. (IPCC 2007)

Principally, there are two ways of mitigating the impacts of climate change. First, it is possible to adapt to the change by preparing communities to withstand extreme weather events, such as heat waves, dry spells, heavy rainfalls and floods. While adapting to the change as such is a worthwhile effort for each country and community, the effects of climate change will, over time, increase to such proportions, e.g. they will affect the availability of water and food production for hundreds of millions of people, that adaptation measures will no longer be sufficient and further solutions will have to be found.

The second principal way to mitigate the impacts of the climate change is to control the drivers behind the changing climate. The main greenhouse gas emissions will remain effective in the atmosphere for up to 100 years or more, permeating the entire atmosphere. The extent of warming depends on the total volume of atmospheric greenhouse gases, and limiting this volume will require a strong and sustained global effort.

The international community is committed to efforts to mitigate climate change. In 1992 in Rio de Janeiro the United Nations Framework Convention on Climate Change (UNFCCC) was adopted. Its ultimate objective is to stabilise greenhouse gas concentrations in the atmosphere at a level that prevents dangerous human interference with the climate system. The Convention is complemented by the 1997 Kyoto Protocol, which sets emission reduction targets for industrialised countries for the period 2008–2012. At the Climate Change Conference held in Bali in December 2007, the parties to the UNFCCC decided to launch formal negotiations on a new Emissions Reduction Protocol by the end of 2009. The aim is to reduce emissions from both industrialised and developing countries after the Kyoto period through the implementation of national measures in line with sustainable development. The United States will also be party to the negotiations, even though it withdrew from the Kyoto Protocol earlier. The negotiations are set to be concluded at the Climate Change Conference in Copenhagen.

The European Union has concretised the ultimate objective of the UNFCCC by proposing that the mean global warming should be limited to 2^0C above pre-industrial levels. The aim is to limit the negative impact of climate change to a tolerable level.

The operating environment in an increasingly global world is also changing; capital and goods are moving around the globe, government regulation is being reduced in many areas, and the markets are open to competition. Businesses are operating within increasingly short timelines, especially as a consequence of the present economic crisis, which poses an enormous challenge for the long-term management of environmental effects in both the public and private sectors.

Sustainable development has been widely accepted as the long-term political objective, and reducing greenhouse gas emissions is one aspect of this trend. Minimising environmental effects in general creates further pressure for change for the business community. Reconciling different objectives is not always easy, even when it is a question of environmental issues or emission components.

Climate change mitigation requires a fundamental change in the technologies being used, as well as in economic structures. Such major changes can be analysed with the help of scenarios. They can be used to identify the kinds of technologies that will be needed in the future or to study the implications of proposed climate treaty decisions, such as the burden sharing between countries due to emission reduction. On the other hand, many technical solutions are complex enough that the impact of their introduction cannot be analysed using models that cover the entire energy economy; instead, they must be analysed using detailed life-cycle analyses.

The objective of this article is to consider from the scenario perspective the emission reduction requirements needed to halt climate change and the corresponding implications for the Finnish energy system and energy technology. Finland is a part of the European Union and the policies of the EU play a very crucial role also in the Finnish energy economy.

2. Greenhouse gas concentration and global climate change mitigation

The increased concentrations of greenhouse gases reduce the radiation of thermal energy from Earth to the space, thus causing a perturbation to the planetary radiation energy balance of the Earth. This perturbation is called radiative forcing. Radiative forcing can be interpreted as heating power which slowly warms up the global atmosphere-surface system of the Earth.

The global atmospheric concentration of carbon dioxide (CO_2) has now exceeded 383 ppm (parts per million). The CO_2 equivalent concentration of other Kyoto gases, primarily methane (CH_4) and nitrous oxide (N_2O), is approximately 50 ppmCO_2-eq. (parts per million in carbon dioxide equivalents). The concentration corresponding to a temperature increase of 2°C is 450 ppmCO_2-eq, based on the IPCC's best estimate of climate sensitivity. The current concentration growth rate is approximately 2 ppm/year, which means that the CO_2 equivalent concentration of Kyoto gases will reach a level of 450 ppm in approximately ten years.

The CFC gases also exert a warming effect on radiative forcing. Including the existing concentrations of CFC gases in the atmosphere, the CO_2 equivalent concentration is currently about at 460 ppm, i.e. above the level corresponding to the 2°C warming effect. In practice, the warming trend is being slowed by anthropogenic particle emissions, which reduce radiative forcing by reflecting incoming solar radiation and the theoretical CO_2 equivalent concentration, and by the enormous heat capacity of the oceans.

However, climate sensitivity is not yet fully understood. It is expressed as the equilibrium warming effect due to the CO_2 equivalent concentration stabilised at 550 ppm, which is twice the pre-industrial level. While the IPCC's best estimate is 3°C, the uncertainty range is significant, 2–4.5°C, and even higher values are not completely out of the question (IPCC 2007). Thus the concentration level of 450 ppm (which, according to the best estimate, corresponds to a warming effect of 2°C) may actually mean an increase of 3°C or even higher in the long term.

Global greenhouse gas emissions are presently almost 50 Gt in carbon dioxide equivalents (Fig. 1). The largest emission source is energy production, but transportation, the buildings sector and industry are also important sources. Large amounts of CO_2 are also emitted from deforestation in tropical countries. Agriculture emits a considerable amount of methane from animal husbandry and nitrous oxide from the use of nitrogen fertilisers. Methane is also emitted from waste management, especially from landfills.

The CO_2 emissions from fossil fuel use (Fig. 2) have grown considerably since the beginning of the 20th century. The present industrial countries have been the main source, although the emissions of the developing countries have also been rising since the mid of the century. The increase of emissions from the developing countries was strong especially in China and India during the economic boom that preceded the present slowdown. During the boom years global emissions exceeded the emissions of the IPCC's long-term scenarios, which, however, are not designed to consider short-term economic fluctuations.

According to the results of the IPCC (2007) the objective of limiting the temperature rise to 2°C means that global greenhouse gas emissions would need to be 50–85 per cent below the current levels by 2050 (IPCC 2007) if the best estimate of climate sensitivity is used in the analysis. According to the Stern Review (2006), the cost of emission reduction would remain clearly below the economic cost of uncontrolled climate change.

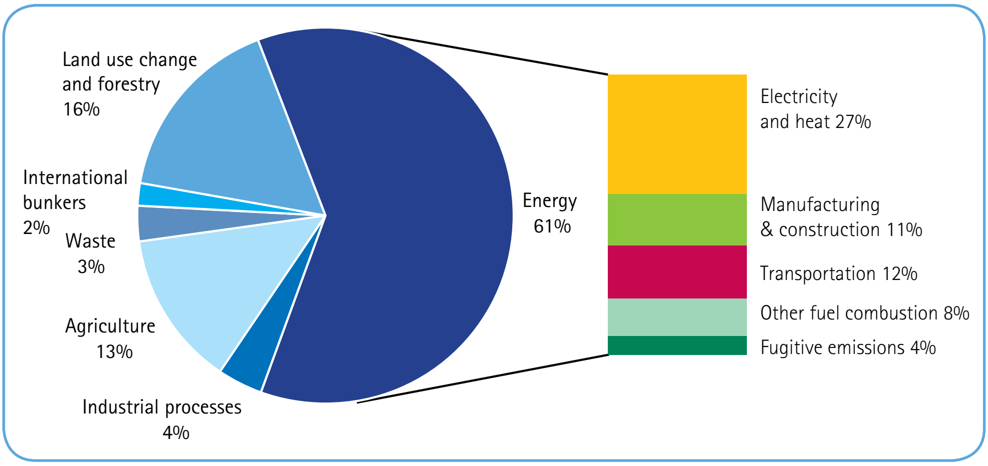

Figure 1. Global greenhouse gas emissions by sector in 2005. The emissions add up to approximately 46 000 $MtCO_2$, the uncertainty of e.g. land use and forestry sector as well as agriculture sector are considerable. Data source: CAIT, cait.wri.org *) The estimated effect of land use change & forestry, 7 600 $MtCO_2$, is for the year 2000.

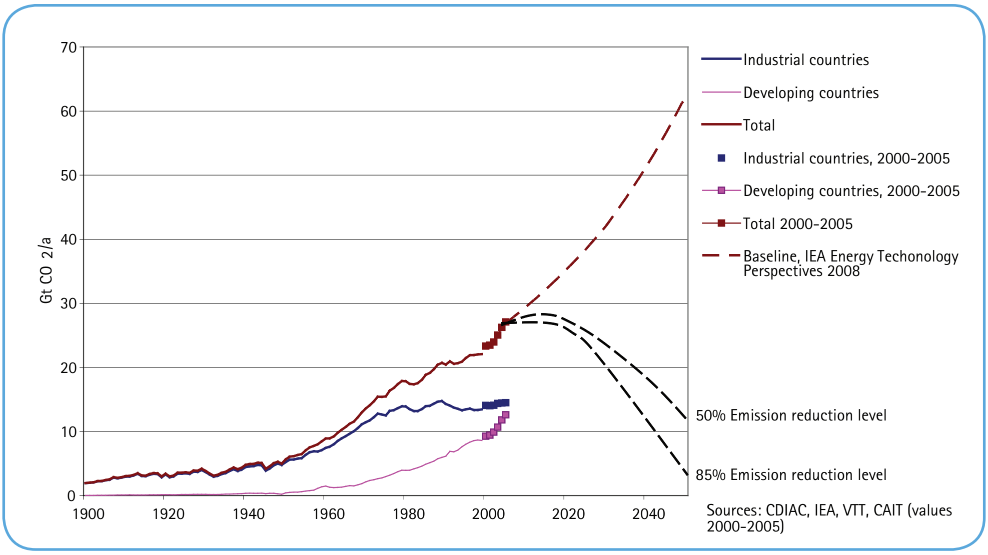

Figure 2. CO_2 emissions from fossil energy use for industrial countries (Annex-1) and developing countries (other than Annex-1 countries). Emission history for 1900–2005 and emission reduction scenarios for limiting emissions by 50% and by 85%, corresponding to upper-limit and lower-limit emissions for a temperature rise of 2 ^{0}C according to the IPCC (2007).

3. Burden sharing

A marked reduction in global greenhouse gas emissions can only be achieved if all significant emitters (countries or country groups) implement efficient emission reduction measures. Thus a broad consensus should be reached concerning climate treaties. On the other hand, there are considerable country-specific differences in the financial capacities, development trends and per capita emissions. Several research organisations and universities have developed models for sharing the burden of global emission reduction targets among different countries and country groups.

VTT has combined various emission allowance calculation principles, or burden-sharing models, in a model describing global emissions and energy economy. Figure 3 shows the projected implications of two different concentration objectives and two burden-sharing models for the targeted reductions for different country groups. A concentration level of 450 ppm corresponds to a warming effect of approximately 2°C and a level of 550 ppm to 3°C, using the IPCC’s best estimate for climate sensitivity.

The Triptych method uses certain criteria to allocate emission restrictions between sectors. In the Multistage model, countries are classified into different categories based on their per capita emission levels and wealth; each category has specific emission reduction obligations. As a country's economy develops, it must adopt tighter emission-reduction targets. The energy system model results show that cost-effective emission reduction requires emissions trading or some other mechanisms for financing reduction measures in developing countries.

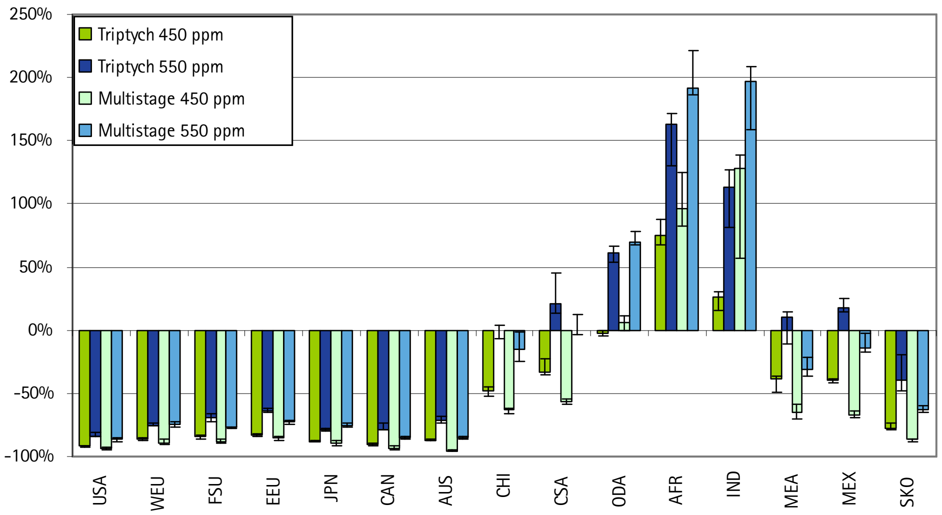

Figure 3. Greenhouse gas emission reduction from the 1990 level by 2050 aimed at atmospheric CO_2, CH_4 and N_2O stabilisation at 450 or 550 ppmCO_2-eq, when using the Triptych or Multistage model for burden sharing. The reduction targets for Western Europe (WEU) and Eastern Europe (EEU) would be of the magnitude of 75–90% and 65–86% respectively, depending on the concentration objective and burden-sharing model. India (IND) and Africa (AFR) could increase their emissions, while China (CHI) should reduce its emissions in the tighter concentration objective scenario. The stabilisation levels of 450 or 550 ppmCO_2-eq correspond roughly to global temperature rises of 2 and 3 ^{0}C, respectively (Ekholm et al. 2008).

The IPCC (2007) estimates that the industrial countries would have to reduce their emissions by 80–95% by 2050 and by 25–40% by 2020 if the objective is to limit the atmospheric greenhouse gas concentration to about 450 ppmCO_2-eq. The emissions from the developing countries in all regions would also have to be clearly lower than the emission baselines by 2050.

The European Union has announced its readiness to cut emissions by 30 per cent from the 1990 level by 2020 if other industrialised countries also proceed with corresponding reductions. The EU has unilaterally undertaken a commitment to reduce emissions by 20 per cent, and has also proposed indicatively to cut its emissions by 60–80 per cent by 2050.

Finland is a part of the European Union. The economic policy and the energy and climate policies of Finland are influenced by the corresponding policies of the EU. The main EU programme to control greenhouse gas emissions within the EU is the Emission Trading Scheme (ETS). After the Kyoto period, starting from the year 2013, the ETS will be mainly administrated directly by the EU, not by member states. There will also be no emission quotas for the ETS sector by EU member states but for the entire EU only.

However, the non-ETS sector emissions should be controlled by member states. A preliminary burden sharing of the emission from the non-ETS sector has already been done for the member states, which corresponds to a total unilateral emission reduction target of 20%. This burden sharing was based mainly on the economic output per capita, and no detailed information on the national conditions of non-ETS sectors was taken into account.

4. Energy system model for scenario considerations

The TIMES model (e.g. Lehtilä et al. 2008, Syri et al. 2008, Ekholm et al. 2008) is a partial equilibrium bottom-up energy system model with a detailed description of different energy forms, resources, processing technologies and end-uses, while taking projections for the rest of the economic system as external projections. The model has versions for the global energy system and for the Finnish energy system.

Commodity prices and consumption are endogenously determined by a supply-demand equilibrium throughout the energy chain. The price of producing a commodity affects the demand of that commodity, while at the same time the demand affects the commodity’s price. The equilibrium has the property that the total consumers’ and producers’ surplus is maximised. The model is thus very suitable for assessing the effect of the energy system alone on, for example, greenhouse gas emissions or industrial development, holding other factors constant. The model version used for Finland has an explicit description of the many demands in physical units, e.g. building volume to be heated by building type, and demand for transport by person-kilometre or tonne-kilometre and transport mode. Furthermore, the energy saving potential is also described by technological measures and costs.

Given the input data on technological development, resource availability and different end-use demand projections, the model calculates the resulting scenario as a minimum of total system cost, including plant investment, commodity and process activity costs, and also the cost of lost demand due to commodity price hikes. This can also be interpreted as representing the maximisation of consumer and producer surplus under the efficient market hypothesis. The model also assumes perfect information and perfect foresight throughout the time horizon. Thus, the model does not take account of game theory set-ups such as competition or conflicts of interests. In this respect the scenarios might not necessarily be sound and reliable predictors of reality, but rather optimal trajectories of how decisions should be made in order to maximise consumer and producer surplus while satisfying all the demand projections and other constraints.

A policy scenario study is initiated by forming a baseline scenario, which describes a business-as-usual trajectory with appropriate projections for drivers and energy demands. Then an alternative policy scenario, in which, for example, the amount of emissions or usage of certain technologies are constrained in a desired way, is calculated.

5. Emission reduction scenarios for Finland

In this article, based on Lehtilä et al. (2008), the Finnish energy economy and other greenhouse-gas-emitting sectors are seen as a part of the EU aiming to reduce its emissions. The main signal for emission reductions is assumed to be the price of emission rights in the ETS. This price controls the emissions within the plants which are part of the ETS. In practice the model assumes that emission reduction measures are implemented until it is cheaper to buy emission rights from the market. This rule is applied also to the non-ETS sector in Finland. It implies that emission reduction measures are implemented also in the non-ETS-sector until the marginal cost level given by emissions trading is reached. The calculations are made for several ex ante given emission rights price levels, as it is very difficult to forecast the behaviour of the ETS price in advance.

The model studies based on long-term scenarios of economic development and emission reduction requirements indicate that the price of emission rights in 2020 might be in the order of 20–50 €/tCO_2 and by 2050 it could rise up to 100 €/tCO_2. (e.g. Koljonen et al. 2008). However, the real price is affected by demand and supply of the rights, which are very difficult to estimate. Economic booms and recessions have impacts on the factors influencing administrative and political decisions e.g. on the possible enlargements of the geographic area and sectoral coverage of the emissions trading system. Furthermore, possible extension and development of the Clean Development Mechanism (CDM), which produces Certified Emission Reduction (CER) units that can be bought to the ETS, also have an impact on the price level of ETS. The tendency might be to finance the emission reduction in developing countries by CDM, which may lower the price level of ETS. On the other hand, big developing countries like China may try to control the price of CERs to follow the ETS level.

The input for the TIMES model runs (Lehtilä et al. 2008) is the economic output scenario obtained from the Ministry of Employment and the Economy in spring 2008. The GDP of Finland is assumed to grow from the present level of about EUR 150 billion (in year 2000 euros) to about EUR 200 billion by 2020 and to about EUR 340 billion by 2050. The main growth is in private services and the volume of energy-intensive industries is growing only slightly. The prices of fuel imports are based on IEA data and the import and export prices for electricity on the results of VTT's Nordic electricity market model. Climate change is assumed to increase somewhat the potential of renewable energy resources like forest biomass and hydro and wind energy, and it is assumed to reduce the specific demand of heating energy. A more detailed description of the assumptions is given by Lehtilä et al. (2008).

Figures 4 and 5 show the development of the primary energy supply and electricity supply in the basic scenario. In the calculation it has been assumed that until 2014 the price of emission rights is 20 €/t in all cases, but from 2015 to 2045 the price of emission rights develops along a linear pathway up to the price given in the figures (20, 40, 60 or 80 €/t). In the basic scenario the amount of nuclear power is limited to the five reactors now in operation or under construction and to the later replacement of the two old pressurised water reactors.

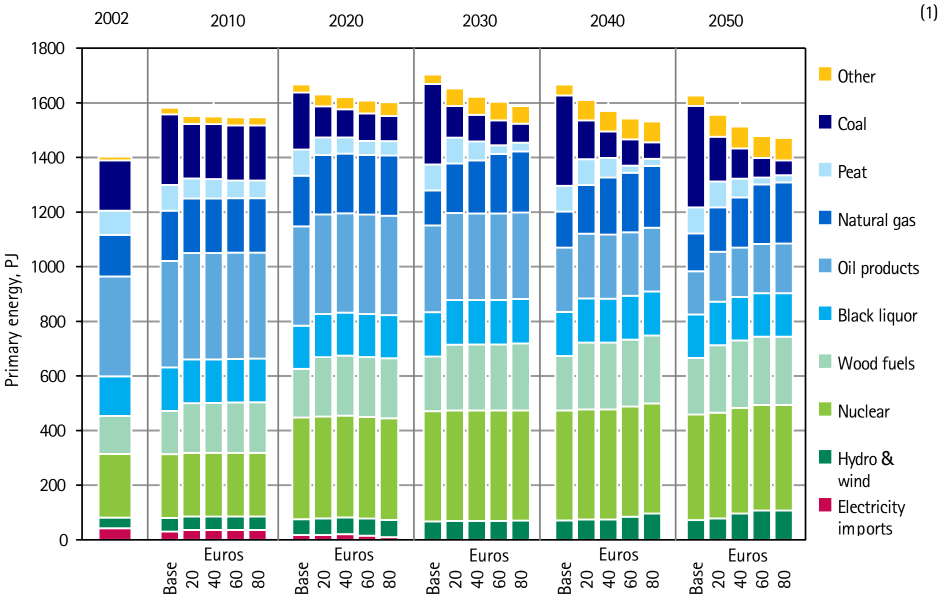

Figure 4. Primary energy supply in Finland by source in the basic scenario. A high emission price leads to a reduction in the use of coal, peat and oil. Emission prices refer to the year 2050; linear rises from the present level are assumed (Lehtilä et al. 2008).

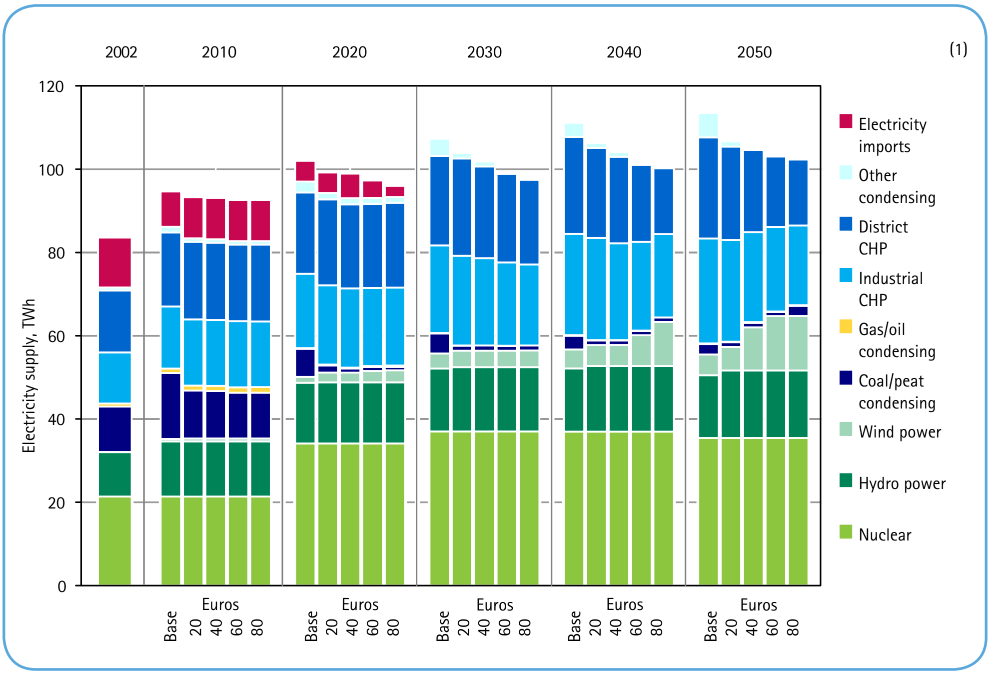

Figure 5. Electricity supply in the basic scenario. Fossil-based condensing power production is replaced by nuclear. A high emission price increases esp. wind power. In the efficiency scenario the electricity supply remains below 100 TWh/a.

In addition to the basic scenarios presented in the figures, also efficiency scenarios are considered by Lehtilä et al. (2008). The basic scenario assumes a moderate improvement rate in the efficiencies and costs of technologies, whereas the efficiency scenario assumes a faster improvement. The specific assumptions are based on Savolainen et al. (2008). In addition, a sensitivity study was made concerning the energy-saving potential. It was assumed that the payback time for energy-saving investments was longer than regularly assumed. This assumption resulted in extensive use of saving measures, which can be interpreted to mean that support of energy-saving investments is profitable for society.

The share of renewable energy in total final energy will exceed 38% in 2020 according to the reference (Lehtilä et al. 2008) in the efficiency scenario and also in the basic scenario if the emission price is on the high pathway. Carbon capture and storage (CCS) will be utilised from the year 2030 onwards in CHP-production of electricity and heat on high emission price pathways.

In Figures 6 and 7 the emissions from energy production decrease strongly as a function of the emission price. Also the emissions in other classes of the figure show a considerable relative decrease, although not so strong as energy production and industry. The measures in the road transport sector are relatively expensive. It has been assumed in the calculations that a transition from fossil gasoline and diesel to biofuels and electric cars takes place during the considered period before the year 2050. In the efficiency scenario the emission reduction achieved at an emission price of 80 €/t is about 66%.

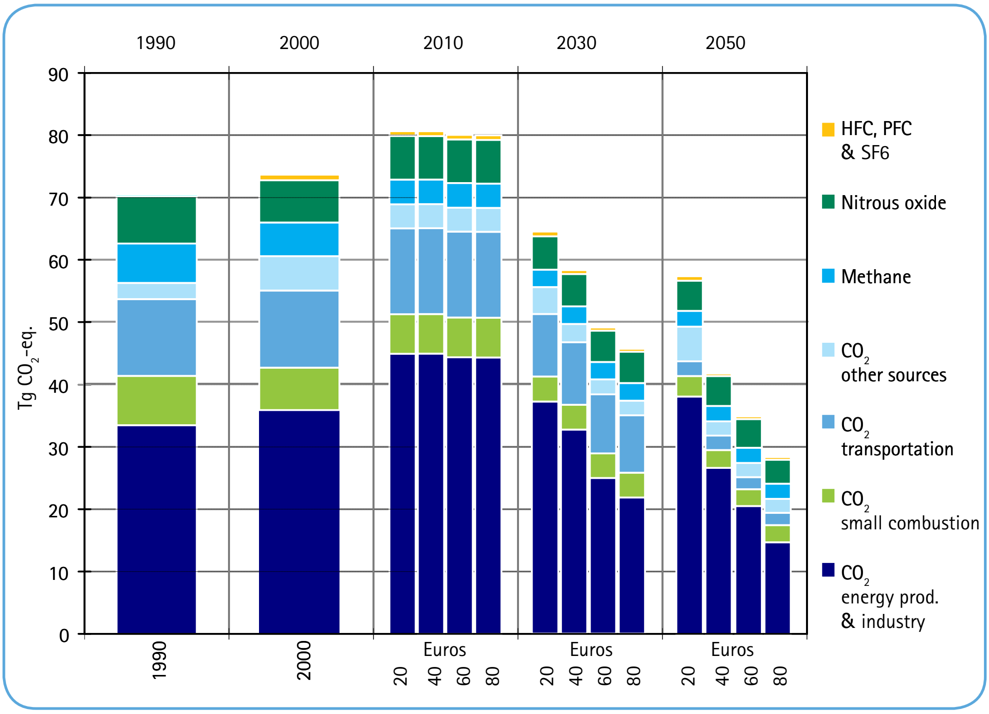

Figure 6. Greenhouse gas emissions in the basic scenario. Increasing the emission price strongly reduces especially the CO_2 emissions from the energy system. The total emission decrease is 60% from the year 1990 level by 2050 if the emission price rises to 80 euro/tCO_2eq.

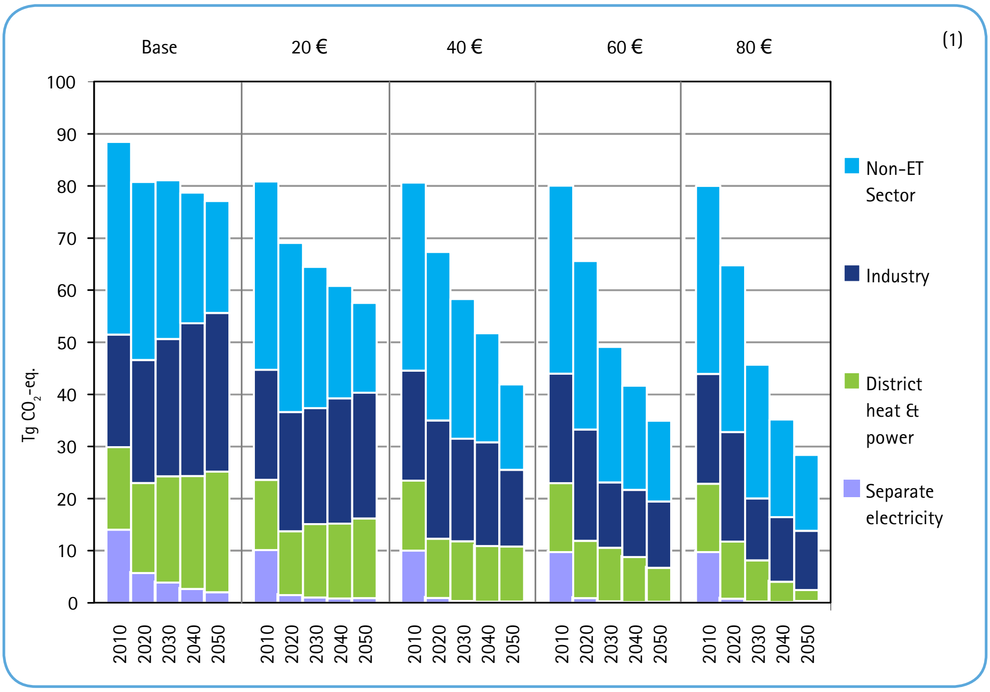

Figure 7. Emissions by sector. Greatest emission reduction takes place in separate electricity production and in district heat and power.

The non-ETS sector has clearly less relative potential for emission reduction (Figure 7). Also, the implementation of the measures requires many instruments such as changes in building codes, support for efficiency improvements in renovations of buildings, information on the efficiency of consumer electronics and household appliances, and regulation of the transport sector. In the calculation model some sectors, such as agriculture, have quite a limited number of emission reduction measures as well as quite limited total emission reduction potential. It might be possible to develop more emission reduction practices and techniques in the coming decades.

The electrification of the society is likely to continue (Figure 8). The share of electricity in total final energy use will grow according to the results of Lehtilä et al. (2008). When the greenhouse gas emissions from electricity generation decrease, the generated electricity might be used even for reducing greenhouse gas emissions in other sectors. Use of electricity often results in good overall energy efficiency, e.g. in plug-in or electric cars, or good economic efficiency, e.g. near-zero-emission buildings (passive houses) where the need for external heating energy is so small that not even district heat is economically viable.

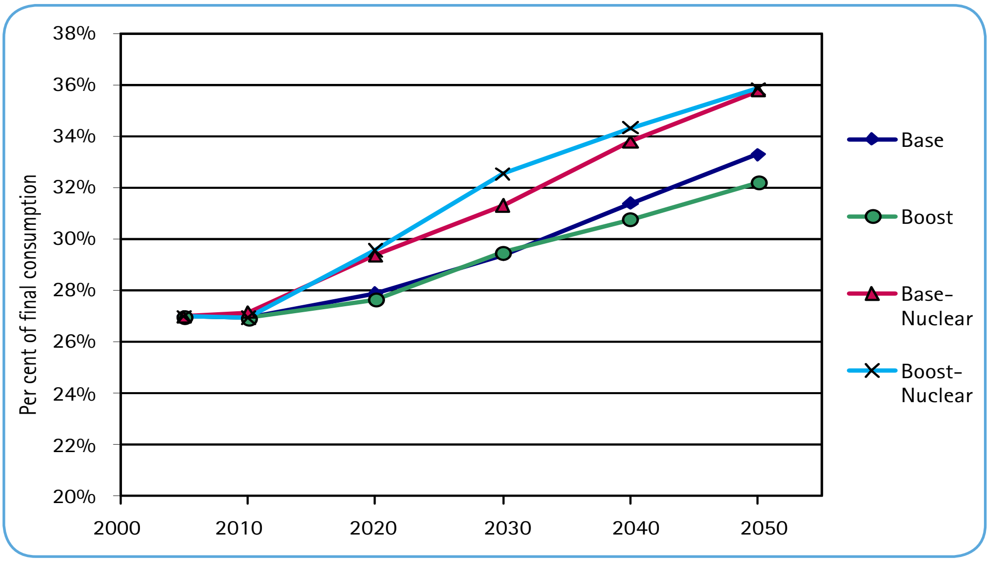

Figure 8. Share of electricity in total energy final use. The price of emission rights is assumed to rise linearly to 60 €/tCO_2 by 2045. The share of electricity rises from the present level of about 27% to 32–35% by 2050, depending on the scenario.

6. Discussion and conclusions

The objective of this article is to consider from the scenario perspective the emission reduction requirements needed to halt climate change and the corresponding implications for the Finnish energy system and energy technology. Finland is a part of European Union and the policies of the EU play a very crucial role also in the Finnish energy economy.

The results presented in this article are scenarios. The real development has a lot of uncertainty mainly due to unstabilised climate policies and regulation in the international and European regime, energy and emission right prices, and growth rates and fluctuations. In the long term there is uncertainty due to factors such as poorly understood atmospheric processes reflecting on climate sensitivity, renewable energy and efficiency improvement potentials, technological developments and the global economy.

If the global temperature rise is to be limited to 2 °C compared with the pre-industrial temperature level, global greenhouse gas emissions will have to be reduced by 50–85 per cent from the current levels by 2050, according to the IPCC. Furthermore, the industrial countries will have to cut their emissions by 80–95% by 2050 and by 25–40% by 2020 to achieve this warming limit. The European Union has announced its readiness to cut emissions by 30 per cent from the 1990 level by 2020 if other industrialised countries also proceed with corresponding reductions. The EU has unilaterally undertaken a commitment to reduce emissions by 20 per cent, and has also proposed indicatively to cut its emissions by 60–80 per cent by 2050.

The new climate policy will have a large impact on future investments in the energy sector in Finland (Lehtilä et al. 2008). There will be a great increase in bioenergy, wind energy and efficiency improvements. In about 2030 some fossil-fuel-fired energy production will be equipped with CCS if the price of emission is high enough. There will be a strong decrease of greenhouse gas emissions in the sectors of condensing-based electricity production, district heating, transport and separate heating. Most of the emission reduction will take place in ETS rather than in the non-ETS sector.

The direct costs of reducing emissions in Finland by 60% from the reference level of 1990 by 2050 are estimated to be between EUR 1 and 2 billion annually, depending on the scenario. The direct costs consist of emission reduction costs and emission rights. This amount is less than 0.6% of the projected GDP in 2050. Efficiency improvements and increased use of nuclear power will lower the costs considerably, according to Lehtilä et al. (2008).

However, it is likely that the global and European emission reduction policies will also cause many side effects. Less use of fossil fuels will reduce the dependency on fossil oil and its fluctuating price. The use of domestic renewable resources will increase, which will create jobs especially in rural areas. The fast-evolving markets for new energy technologies will also create opportunities for Finnish R&D and manufacturing companies (Koljonen et al. 2008).

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Role of nuclear energy in mitigation of climate change

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1. Introduction

World annual primary energy consumption is currently about 12,000 Mtoe (BP 2008, IEA 2006) and it seems inevitable that it will rise in the coming years (Fig. 1).

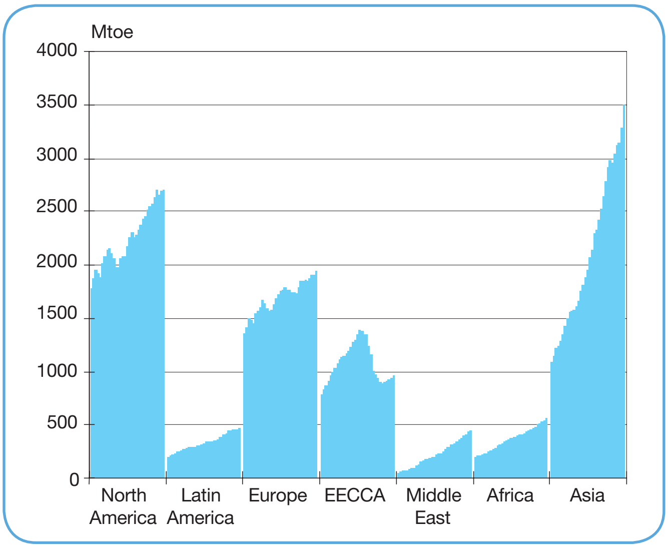

Figure 1. Global annual primary energy demand (including traditional biomass),1971 – 2003 by region. Note: EECCA = countries of Eastern Europe, the Caucasus and Central Asia. 1000 Mtoe = 42 EJ (IEA 2004, IPCC 2007).

The increase is largely due to social and economic development in fast-growing countries like China and India, but the trend is also evident in the OECD countries as well as in less-developed parts of the world. CO_2 emissions have increased continuously in most parts of the world, which is not a sustainable development from the climate point of view (Fig. 2).

Around 40% of primary energy is used to generate 18,000 TWh of electricity annually. Globally, 16% of this amount is produced with nuclear power. In the OECD countries the share is 26% (Fig. 3). It is estimated that by 2050 total electricity production will increase by a factor of about 2.5 (NEO 2008).

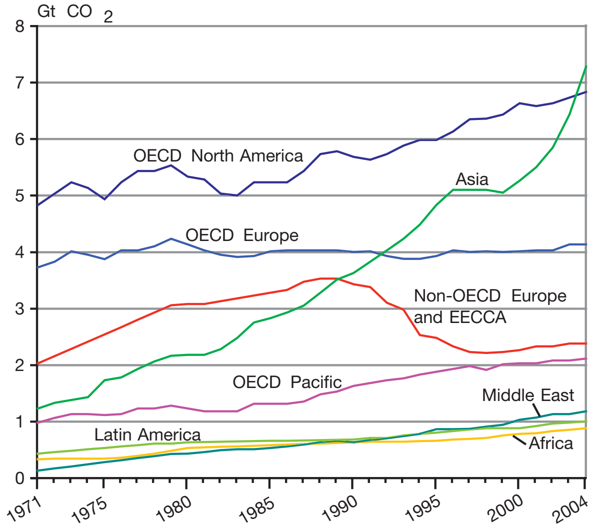

Figure 2. Global trends in carbon dioxide emissions from fuel combustion by region from 1971 to 2004 Note: EECCA = countries of Eastern Europe, the Caucasus and Central Asia (IEA 2006, IPCC 2007).

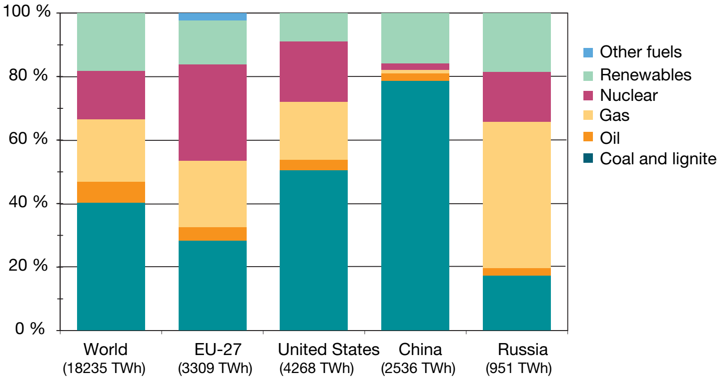

Figure 3. Share of electricity production by fuel type in 2005 in different regions.

Because electricity generation currently produces about 27% of the man-made CO_2 emissions and is the fastest growing source of greenhouse gases, attention is being paid to making the production increasingly carbon neutral or free. One option for approaching the target is to maintain or strengthen the role of nuclear energy.

2. Role of nuclear power in sustainable energy production

Nuclear fission is a major source of energy and practically free from CO_2 emissions. In 2007, 2608 TWh of electricity was generated by nuclear power. As of January 2009, 436 nuclear power plants were in operation with a total installed capacity of 372 GWe (WNA 2009) in 31 countries, with the largest capacity in Europe, the USA and Southeast Asia (Fig. 4). The US has the largest number of reactors and France the highest share of total electricity generation. Non-electricity applications are few at present, but include process heat, hydrogen production, ship propulsion, and de-salination.

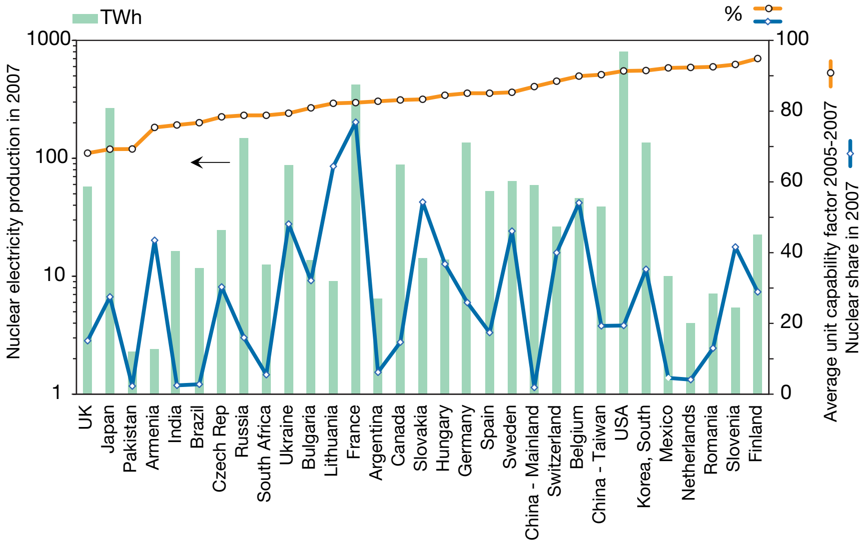

Figure 4. Nuclear energy producing countries.

World projections

Nuclear power has long been controversial, especially in Europe, with concerns over the safety of nuclear installations, radioactive waste, and proliferation of nuclear weapon materials. Globally, however, renewed interest in nuclear energy has been sparked by concerns for energy security, economic development, and commitment to reduce CO_2 emissions. Nuclear power is not susceptible to even large fuel price fluctuations as it is based on uranium sources that are widely distributed around the globe, and fuel supply is not strongly affected by geopolitical issues. In addition, because many years' worth of nuclear fuel can be stored in a small area, the presence of local uranium resources is not a pre-condition for nuclear energy security. In much of the industrialised world, nuclear is a presently available base-load option that combines low carbon emissions with the potential for rapid large-scale expansion.

Ambitious plans for new nuclear builds have been announced by China, India and Russia, while many other countries are considering nuclear power as well. Currently, 41 power reactors are being constructed in 9 countries, notably in China, South Korea, Japan and Russia. Many more reactors are either planned (108) or proposed (266), mostly in China, India, Japan, Korea, Russia, South Africa and the US (WNA 2009). In the US the Department of Energy (DOE) has recently presented three scenarios for nuclear capacity in 2030 (NEAC 2008). In the low scenario the operating life of all the present reactors would be extended to 60 years, in the middle scenario 17 GWe of new capacity would be added, and in the high scenario 45 GWe of new capacity would be added. The industry's expectation coincides with the high scenario with announced plans for 30 potential new reactors in the USA.

The International Atomic Energy Agency (IAEA) estimates that nuclear power will expand by 17–46% up to 2020 and by 27–100% by 2030 (IAEA 2008a). In the Nuclear Energy Outlook of 2008 the Nuclear Energy Agency of OECD has projected the global nuclear capacity to increase by a factor of between 1.5 and 3.8 by 2050: i.e. up by 600 GWe to 1400 GWe.

Improved safety and economy as well as improved use of fuel resources are objectives of new reactor designs. Worldwide operational performance has improved and the average unit capability factor in 2005–2007 was 83.5% (IAEA 2008b). Key issues determining the prospects for a large expansion of nuclear energy are costs, safety, waste management, and proliferation risks; all must be resolved satisfactorily to ensure public acceptance. Political risks – energy policy changes, regulatory uncertainties, and financial risks in a liberalised energy market – will also affect the rate of nuclear expansion. A critical issue in many developing countries, but also important everywhere, is the need for education and training to maintain competence in the construction and operation of nuclear power plants.

In Europe, a recent Green Paper on energy development in Europe by the European Commission emphasised that the priorities are sustainability, security of supply, and competitiveness. Both nuclear and renewables are acknowledged as important energy resources, now and in the future. The EU's Action Plan to combat climate change by 20% acknowledges the significant role of nuclear energy in cutting greenhouse gas emissions by 2020. However, the member states are free to choose their own energy mix.

Economic competitiveness and cost trends

The economic competitiveness of nuclear power depends on plant-specific features, the number of plants previously built, annual hours of operation and local circumstances. Full life cycle cost analyses have been used to compare nuclear generation costs with coal, gas, and renewable systems (IEA/NEA 2005), including (Fig. 5):

- investment (around 45–70% of total generation costs for design, construction, refurbishing, decommissioning and the expense schedule during the construction period);
- operation and maintenance (around 15–40% for operating and support staff, training, security, and periodic maintenance); and
- fuel cycle (around 10–20% for purchasing, converting and enriching uranium, fuel fabrication, spent fuel conditioning, reprocessing, transport and disposal of the spent fuel).

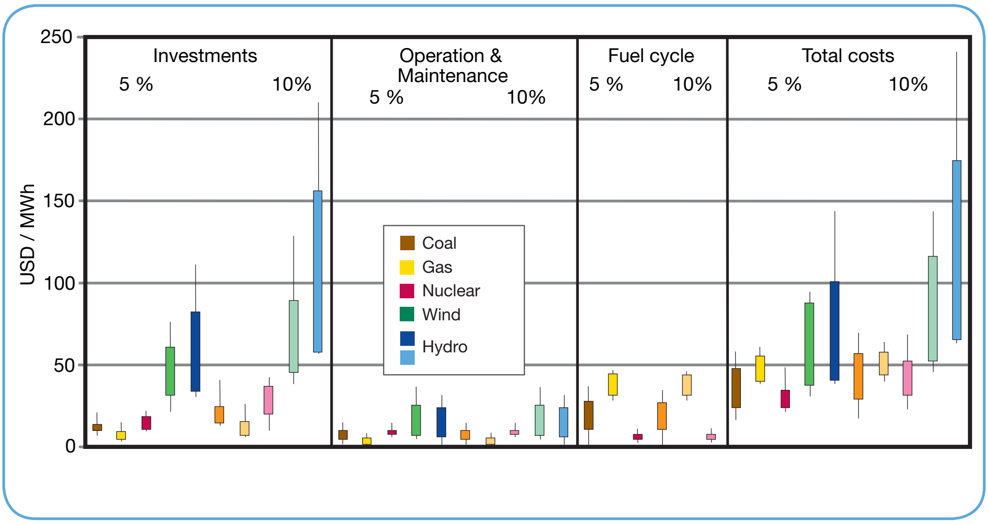

Figure 5. Projected costs of generating electricity, coal, gas, nuclear, wind and hydro with interest rate 5% and 10% (IEA/NEA 2005). Note: Bars depict 10 and 90 percentiles and lines extend to show minimum and maximum estimates.

The most important elements affecting the availability of a nuclear power plant are the duration of annual refuelling outages and undisturbed operation. Therefore, special attention is paid to the planning and technical implementation of annual refuelling outages and the reliability of plant systems. In the Finnish nuclear power plants the length of refuelling outages has been optimised. For example, the length of annual outages in Olkiluoto 1 and 2 units have varied from 7–8 days (refuelling outage) to 12–14 days (maintenance outage). When major modifications are needed, the outage length is around 20 days. Recently, similar reductions in outage duration have been achieved in other countries as well, resulting in a steady increase in the average capacity factors.

Furthermore, the modernisation of the Finnish NPP units has fulfilled most of the advanced safety requirements applicable to new nuclear power plants in Finland. The net output of units 1 and 2 at Olkiluoto has altogether been increased from 660 MW to 860 MW (30%) by uprating the thermal power and increasing the thermal efficiency. Plant modifications have been successful. The average capacity factors during 1995–1998 and after the modernisation program (1999–2001) have been

94.1% and 96.2%, respectively. The total generation cost (including capital, O&M, fuel and waste management) after the modernisation has been reduced by one quarter compared with the value before the latest modernisation.

Greenhouse gas emissions of nuclear energy

Total life-cycle GHG emissions from nuclear power per unit of electricity produced are below 40 gCO_2/kWh)–at a similar level to renewable energy sources. It is therefore an effective GHG mitigation option, and also very quick acting by way of investment in the lifetime extension through retro-fitting of existing plants.

The emissions originate mostly from the front-end of the fuel cycle (extraction/leaching, isotope enrichment, and fuel fabrication). The technologies employed in enrichment (gaseous diffusion or centrifuge) have different energy input needs and thus have large variations in emissions. Energy use in the mining stage correlates with the costs of mineral recovery. Based on the life cycle analysis results of (Vattenfall 2005), even in the case of exploiting low-grade ore deposits with 0.03–0.06% uranium content the energy used in the extraction/leaching phase is still low and the CO_2 emissions brought about by mining are only about 1 gCO_2/kWh.

The competitiveness of nuclear and renewable energy production would be further increased if the external costs associated with CO_2 emissions were included. In this regard, a European study (EU 2005) evaluated external costs for a number of power-generation options emphasising the zero- or low-carbon-emitting benefits of nuclear energy and renewables.

Safety of nuclear energy

Despite good economic performance, an excellent safety record in most nuclear energy countries and obvious environmental merits, a lot of controversial opinions exist among the public, and various approaches have been adopted on the country level regarding acceptability of nuclear energy because of safety concerns. The historic accident of Chernobyl will always remind people of the potential dangers of nuclear power, even though it is no longer possible due to changed technology and better understanding. Nuclear safety is a top priority in all the countries using nuclear energy. It is guaranteed by strong national safety authorities, new designs with advanced safety features, commitment to safety among the nuclear power operators, worldwide safety research and very intensive international co-operation. A lot of things still need to be done to maintain and improve safety: regulatory effectiveness and efficiency are being worked on in the international community, efforts are needed to transfer knowledge and good practices to countries considering the nuclear option, and continuous investment in education and training in countries where many senior personnel are retiring.

Proliferation and global nuclear energy partnership

The enrichment of uranium, spent fuel reprocessing, and separation of pure plutonium must be considered in the context of preventing the proliferation of nuclear weapons. The Treaty on Non-Proliferation of Nuclear Weapons (NPT), which has been ratified by nearly 190 countries, operates a safeguard system to control fissile material that may be used in weapons. Compliance with the NPT is verified and monitored by the IAEA. Improving proliferation resistance is a key objective in the development of next-generation reactors and advanced fuel cycles. A recent example of enhanced international efforts is the Global Nuclear Energy Partnership (GNEP) proposed by the USA.

In a once-through fuel cycle, stocks of plutonium build up in the spent fuel, but only become accessible when the fuel is reprocessed. Disposal of spent fuel without reprocessing therefore limits opportunities for proliferation. Recycling through fast reactors considerably increases the utilisation efficiency of uranium, but also introduces opportunities for plutonium to be diverted to non-peaceful purposes. Reprocessing therefore needs careful safeguards. Reducing the possibilities of this undesirable diversion of plutonium and other actinides is a design goal in the development of new reprocessing concepts.

The thorium fuel cycle is more proliferation-resistant than the uranium cycle, since it produces fissionable ^{233}U instead of fissionable plutonium. In addition to ^{233}U, the thorium cycle produces ^{232}U as a by-product, which has a daughter nuclide emitting high-energy photons making the material difficult to handle.

3. Technological opportunities to build nuclear power

Advanced nuclear power concepts

Most nuclear power plants in the USA and Europe have second-generation light water reactors (LWRs), while the plants now being built in Southeast Asia are of a third-generation design. The European Pressurised Water Reactor or Evolutionary Power Reactor (EPR) under construction in Finland by the Areva-Siemens consortium, and the Pebble Bed Modular Reactor (PBMR) being developed in South Africa, are both of types referred to as generation III+. From 2030 onwards, fourth-generation reactors are expected to provide improved fuel utilisation and economy (Fig. 6).

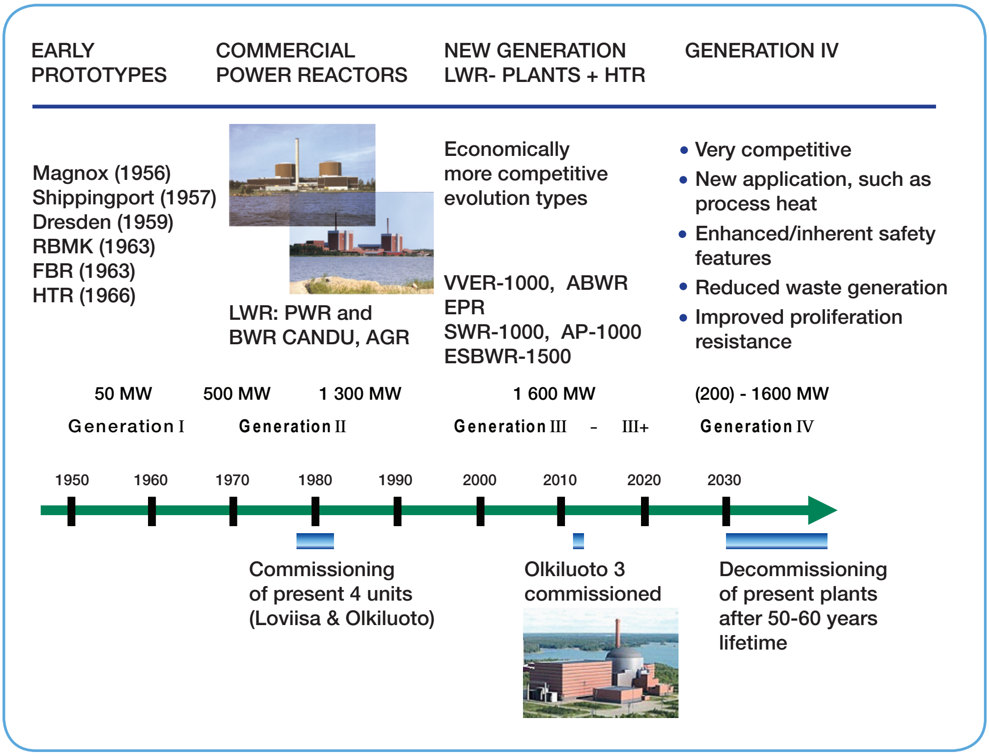

Figure 6. Nuclear power plant generations. Adapted based on (GIF 2002).

Reactor suppliers in North America, Japan, Europe, Russia and South Africa have about a dozen new nuclear reactor types at advanced stages of design, while others are at research and development stage.

The typical features of third-generation reactors include (WNA 2008):

- a standardised design for each type to expedite licensing, reduce capital cost and reduce construction time,
- a simpler and more rugged design, making them easier to operate and less vulnerable to operational upsets,
- higher availability and longer operating life–typically 60 years,
- reduced possibility of core melt accidents,
- resistance to serious damage that would allow radiological release from an aircraft impact,
- higher burn-up to reduce fuel use and the amount of waste,
- burnable absorbers (“poisons”) to extend fuel life.

The PBMR is a high-temperature, graphite-moderated, gas-cooled reactor. It has a high thermal efficiency due to the high operating temperature. The PBMR is characterised by a high level of safety due to the large heat capacity of the moderator. The flow of helium gas coolant is sustained by natural circulation if power to the circulation pumps is lost, so the potential for a destructive loss-of-coolant accident is low. South Africa has an effort under way to exploit the PBMR technology. Similarly in the USA the Next Generation Nuclear Plant (NGNP) prototype employs the VHTR concept, and is based on what is judged to be the lowest risk technology development that will achieve the needed commercial functional requirements to provide an economically competitive nuclear heat source and hydrogen production capability. The reactor core technology will either be a prismatic block or pebble bed concept. The NGNP will produce both electricity and hydrogen using an indirect cycle with an intermediate heat exchanger to transfer the heat to either a hydrogen-production demonstration facility or to a gas turbine. The targeted time schedule is to have the construction of NGNP completed in the early 2020s.

In 2008 there have been parallel processes in Finland by three utilities aiming at building additional nuclear power plant units after 2010. If one or more of these projects is accepted in the Decision-in-Principle process and a construction licence is obtained, there will be at least one more reactor unit, in addition to Olkiluoto 3, in operation before 2020.

Fourth-generation nuclear reactors

Fourth-generation reactors have new and demanding performance goals. These include more efficient fuel use, less waste, better economic performance, improved safety and reliability, enhanced proliferation resistance, and better physical protection. Meeting these ambitious goals requires that substantial efforts are devoted to research, technological development and demonstration of the concepts. The key technologies for generation IV are fast neutron reactors with a closed fuel cycle and high or very high operating temperatures. In 2000, the US DOE launched the generation IV International Forum (GIF 2002), with currently 13 participating countries, including the EU, Russia and China, collaborating on new designs. The Forum is focusing on six designs that face different technical challenges to reach industrial maturity and accordingly have different time schedules. Industrial deployment is foreseen by year 2030 at the earliest for the most advanced systems. The anticipated deployment dates for the six systems vary between 2030 for SFR and VHTR and 2045 for GFR, SCWR, LFR and MSR. Deployment of intermediate systems (i.e. not fully compatible with Gen-IV objectives) may take place on a shorter time schedule.

Four of these reactor concepts are fast reactors, which allow for much improved utilisation of the uranium fuel. The sodium-cooled fast reactor is the most mature technology, and so may be deployed in the medium term. However, additional technology development is needed to further improve safety and to develop high-performance materials. The gas-cooled fast reactor is an attractive alternative to sodium-cooled reactors because of its potential for higher-temperature applications and hydrogen production. The very high temperature reactor, with temperatures above 950°C, is seen as a promising candidate for the production of hydrogen or synthetic fuels (Fig. 7).

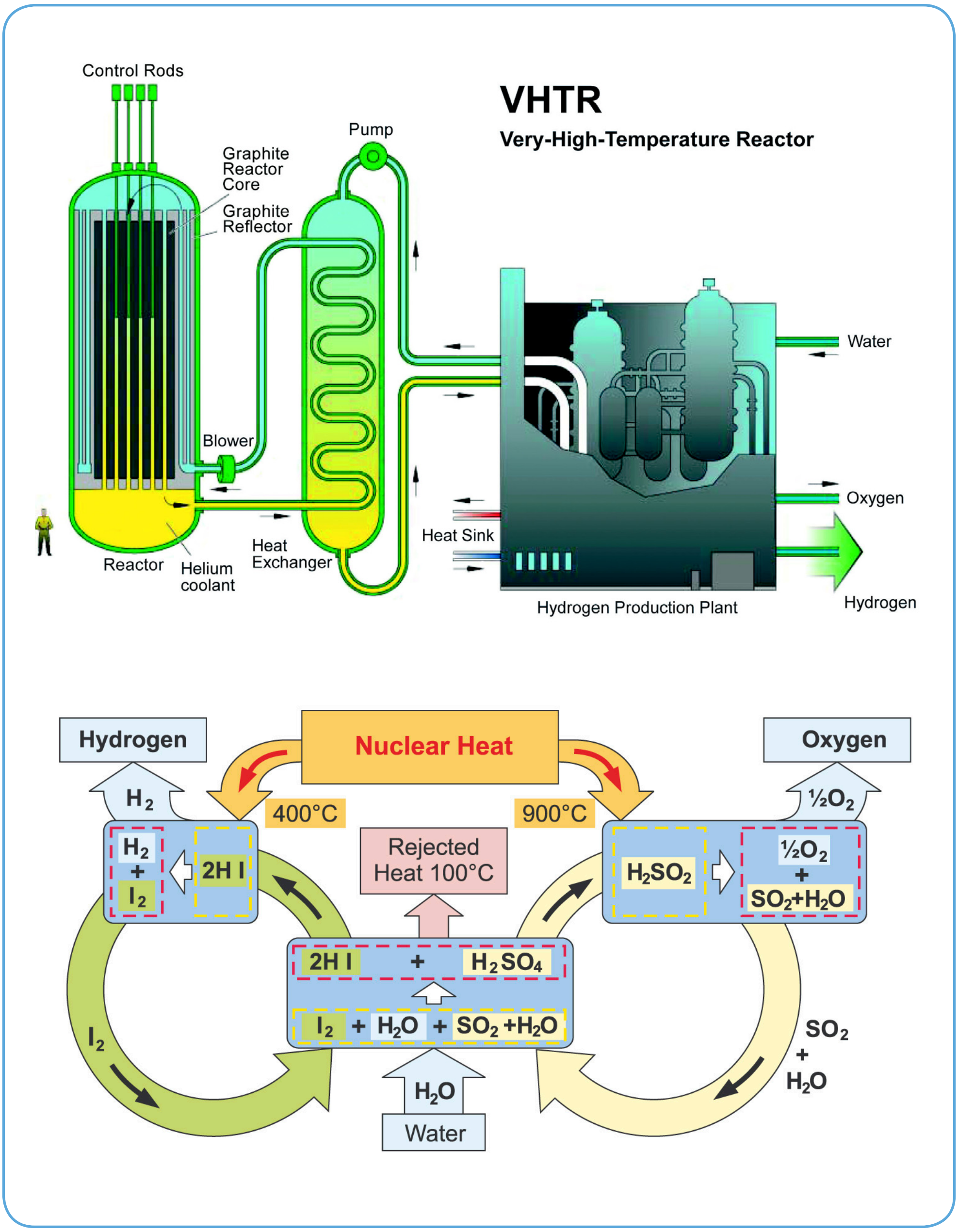

Figure 7. Very High Temperature Reactor (GEN IV) combined to hydrogen generation process.

The supercritical water-cooled reactor design is a further development of the boiling water reactor, aiming at much improved thermal efficiency. Lead-cooled fast reactors are considered to be the most promising for proliferation-resistant nuclear power; Russia has some experience with small (100 MWe) reactors using lead alloys as the coolant. The molten salt reactor is probably the least mature design of the six, but is valued for its potential to operate with a thorium fuel cycle and thus greatly expand the available fuel resources.

The targeted 60-year lifetime for Gen IV reactor systems brings about special technical challenges with regard to materials and components owing to fast neutron damage (on core materials and fuel), and required high temperature and corrosion resistance. Additionally, there are challenges related to design, operation and safety requirements, such as material availability and cost, fabricability, joining technology, in-service inspection, strict safety requirement and licensing as well as decommissioning and waste management methods.

Progress in Europe

The European efforts to develop future nuclear reactor systems and advanced fuel cycle facilities will be performed within the framework of Sustainable Nuclear Technology Platform. The platform was officially launched in September 2007. Future research, development and demonstration (RD&D) will address three objectives: (1) maintain the safety and competitiveness of today's technologies, (2) develop a new generation of more sustainable reactor technologies, i.e. fast neutron reactors with a closed fuel cycle, and (3) develop new applications of nuclear power such as massive production of hydrogen, desalination or other industrial heat processes. The platform has elaborated its Strategic Research Agenda (SRA), which identifies and prioritises the research topics.

The Strategic Energy Technology Plan of the EU (SET plan) identifies fission energy as a contributor to the 2050 objectives of a low-carbon energy mix, relying on a new generation of reactors and associated fuel cycles. This objective is to be achieved by acting now to "complete the preparations for the demonstration of a new generation (Gen-IV) of fission reactors for increased sustainability". This new generation of reactors will not replace the advanced light water reactors which are now being built in Europe. Rather, a two-track, complementary development is envisaged from 2040 onwards, relying on Gen III Light Water Reactors and Gen IV Fast Neutron Reactors to maintain at least the 31% share of nuclear electricity in Europe.

4. Fuel resources – fuel cycle scenarios

Fuel cycle

In the long-term, the potential of nuclear power depends on how effectively the world's uranium resources are used. Today's thermal reactors with a "once-through" uranium fuel cycle use less than 1% of the energy in the fuel; most of this energy comes from the fissile isotope ^{235}U, which makes up 0.7% of natural uranium. Fast reactors – based on fast neutrons instead of thermal neutrons – operating with a closed fuel cycle may effectively utilise also ^{238}U, which makes up 99.3% of natural uranium. In the closed fuel cycle plutonium produced in the fast reactor as well as unused uranium is recycled, so that uranium reserves are used much more efficiently.

To further increase the sustainability of nuclear energy, more efforts should be dedicated to the development of advanced fuel cycles, which have two objectives. The first objective is to further improve the competitiveness of nuclear energy, for instance by designing more efficient cores and fuels to better use the energy content of uranium fuel. The second objective is to reduce the volume, thermal impact, radioactive inventory and longevity of the ultimate waste, which is to be disposed of in a geological disposal site.

Nuclear fuel resources

Estimates of uranium resources vary with assumptions about its use (Fig. 8). Used in typical light water reactors (LWR) the identified resources of 5.5 Mt uranium, at prices up to US$130/kg, correspond to about 2700 EJ of primary energy and are sufficient for about 100 years supply (OECD 2008) at the 2006 level of consumption. The total conventional uranium resources are about 16 Mt (8000 EJ). There are also unconventional uranium resources such as those contained in phosphate minerals (22 Mt), which are recoverable at a cost of US$ 60–100/kg (OECD 2004). The total conventional resources and uranium in phosphate minerals combined amount to 38 Mt (19,000 EJ). With fast-spectrum reactors operated in a "closed" fuel cycle by reprocessing the spent fuel and extracting the un-utilised uranium and plutonium produced, the reserves of natural uranium may be extended in a stationary situation to several thousand years at current consumption levels. In the recycle option, fast-spectrum reactors (FNR) utilise depleted uranium and only plutonium is assumed to be recycled, so that the uranium resource efficiency is increased by a factor of 30 (Fig. 8). If advanced breeder reactors are introduced in the future to efficiently utilise recycled or depleted uranium and all actinides, then the resource utilisation efficiency would be further improved by an additional factor of up to eight (OECD 2006).

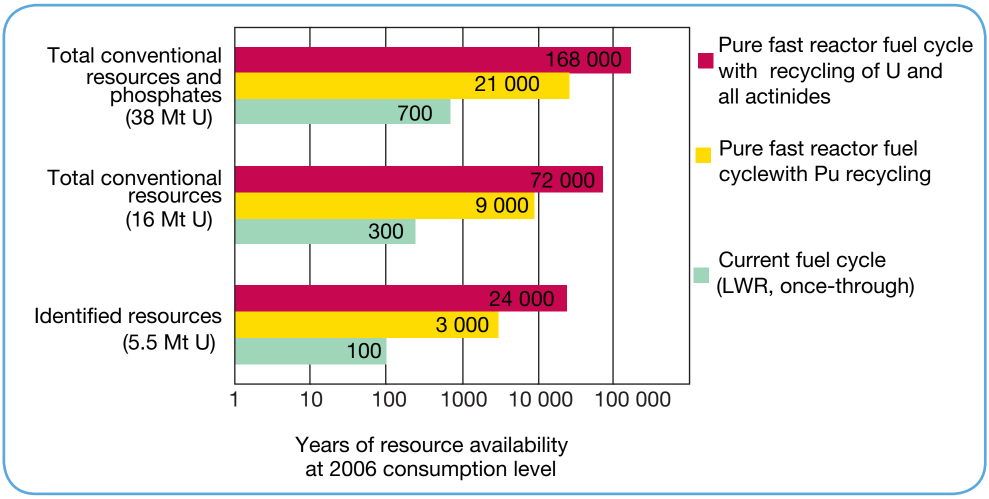

Figure 8. Estimated years of uranium resource availability for various nuclear technologies at 2006 nuclear power utilization levels (OECD 2008, OECD 2001, OECD 2006).

The geographical distribution of identified resources recoverable at a cost of less than US$ 130/kg U is shown in Fig. 9. 60% of uranium is produced in three countries: Canada 23%, Australia 21%, Kazakhstan 16% (OECD 2008).

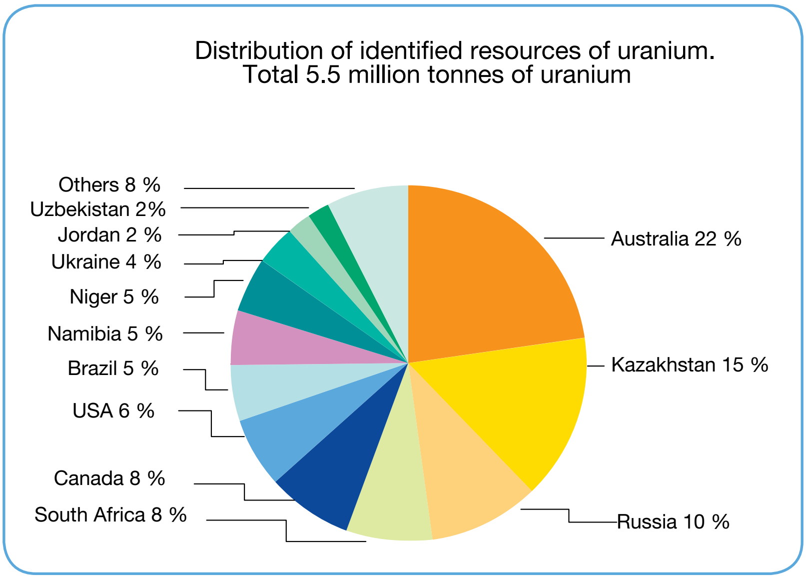

Figure 9. Geographic distribution of identified resources of Uranium.

In the recent years the price of natural uranium has been rather volatile and in mid-2007 the price peaked at 135 USD per pound (lb) of U_3O_8. Since then, the price has declined to a level of 50 USD/lb U_3O_8. which is roughly at the long-term average level expressed in constant 2007 dollar values (Fig. 10).

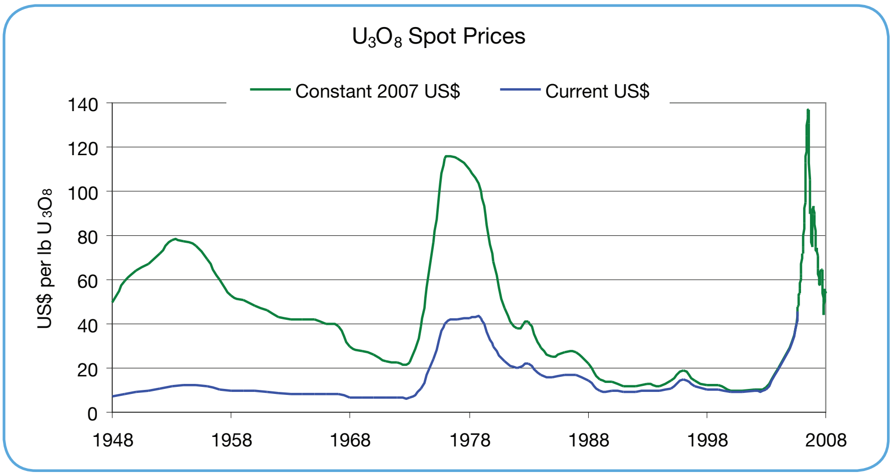

Figure 10. Price history of uranium (The Ux Consulting Company).

Nuclear fuels could also be based on thorium, with proven and probable resources being about 4.5 million tonnes (OECD 2004). Thorium-based reactors appear capable of at least doubling the effective resource base, but the technology remains to be developed to ascertain its commercial feasibility (IAEA 2005). India has large reserves of thorium, but the commercial feasibility of the thorium cycle will remain uncertain until more technical development has been done. A governmental committee in Norway studied the opportunities of using thorium as an energy source and concluded in its final report that the current knowledge of thorium-based energy generation and the geology is not solid enough to provide a final assessment regarding the potential value for Norway of a thorium-based system for a long-term energy production. However, the Committee recommended that the thorium option be kept open in so far it represents an interesting complement to the uranium option to strengthen the sustainability of nuclear energy.

Prospective on global energy demand and nuclear power capacity

The transition from present employment of light water reactors to a situation, where increasing share of nuclear energy is produced by closed fuel cycle in fast neutron reactors, is a dynamic process, the understanding of which requires simulation of prospective nuclear energy scenarios. An early introduction of fast reactors lowers the cumulative consumption of natural uranium resources. In the following key results of simulations conducted in the studies by CEA are presented.

The IIASA scenarios (IIASA 1998) covering the 21st century are used as starting point. In this study they are extrapolated up to 2150.

Two scenarios on global electric energy demand are considered: (1) H (high) based on IIASA-scenario B; Scenario B is a business as usual world growth scenario during the 21st century (around 2% growth per year) and (2) L (low) based on IIASA-scenario C; Scenario C.2 corresponds to a strong will to protect the environment against global warming. Nuclear energy represents around 12% of world demand for primary energy in 2050, which is close to twice as much as today (Fig. 11).

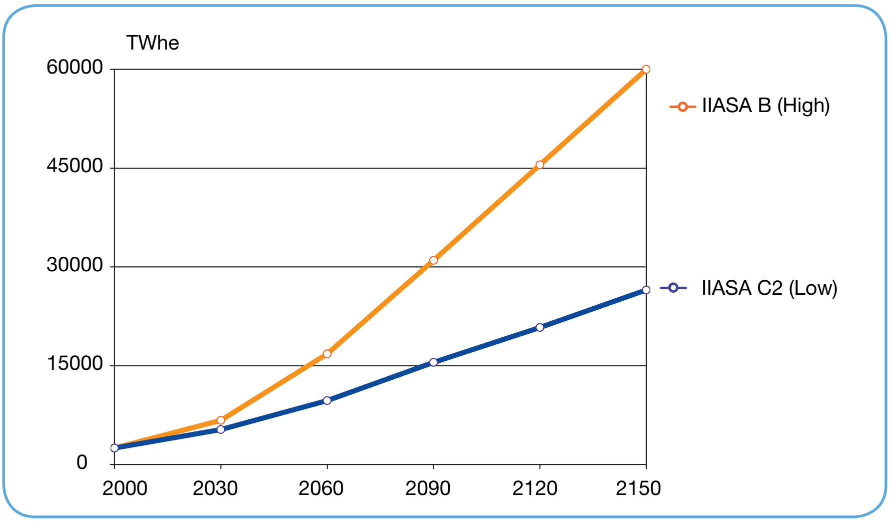

Figure 11. Growth of annual nuclear power production for IIASA scenarios B and C2 (named H and L in this study), (IIASA 1998).

A renewal of nuclear power implies the construction of many new reactors every year, whatever the technology involved. During the latter half of this century, about 40 new reactors would have to be constructed annually for low-demand scenarios and more than 100 for high-energy-need scenarios (Fig. 12).

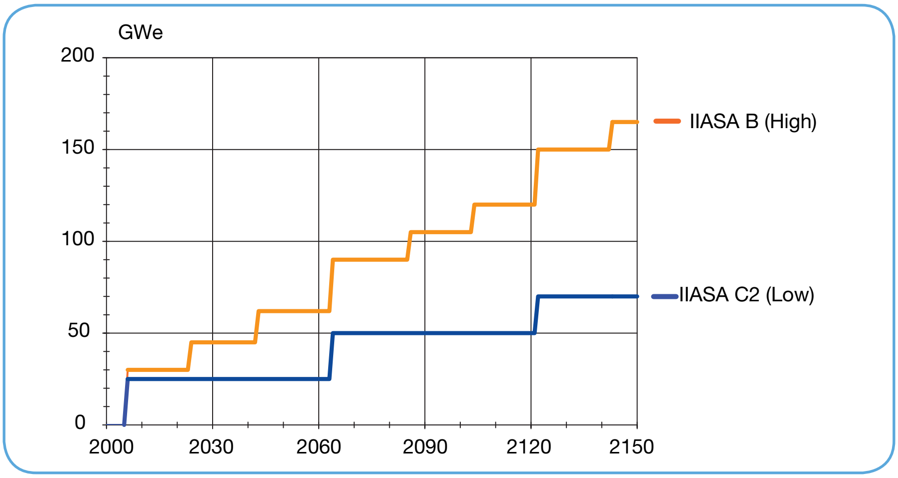

Figure 12. New net nuclear power capacity (in GWe) to be installed annually for IIASA scenarios B and C2, (IIASA 1998).

The key issue is to estimate the extent to which the deployment of fourth-generation nuclear systems could help reduce the cumulative need for uranium. In the following assessment, for simplification, Light Water Reactors utilise enriched natural uranium as the only fuel and Generation IV reactors have Sodium Fast Reactors characteristics and utilise plutonium as fuel.

Natural uranium consumption is evaluated by making the following renewal hypotheses for the current fleet of reactors and the recycling of materials:

- LWRs only: Continuation of an open cycle through the introduction of LWRs only using enriched uranium during the whole 21st century.
- LWR & FNR: Introduction, from 2040 onwards, of “as many as possible” 4th generation Fast Neutron Reactors, using depleted uranium available and recycled plutonium. For these systems, the availability of plutonium is a key factor, which dictates the rate and total capacity that can be installed over time. When not enough plutonium is available, the needed capacity is completed with LWRs.

The quantity called “Natural uranium consumed” represents the cumulative mass of natural uranium consumed by the power plant fleet without adding the future needs of the reactors that are already installed. A second quantity called “Natural uranium engaged” also takes into account the future needs during their remaining lifetime of the reactors in the fleet.

The results of the performed evaluations by CEA (CEA 2008 & 2009), are presented in Fig. 13. If only 3rd generation thermal reactors were to be installed, the cumulative consumption of uranium would amount to 20 to 30 Mt by 2100, and the amount of engaged uranium to 32 to 55 Mt. This would require the availability of total conventional uranium resources (16 Mt) as well as uranium from phosphates (22 Mt). The main constraints will not be necessarily the uranium resources themselves but the possibility to extract, at a reasonable production cost, the uranium contained in low content sources. In all cases, mining exploration will have to be intensified in order to achieve those aims.

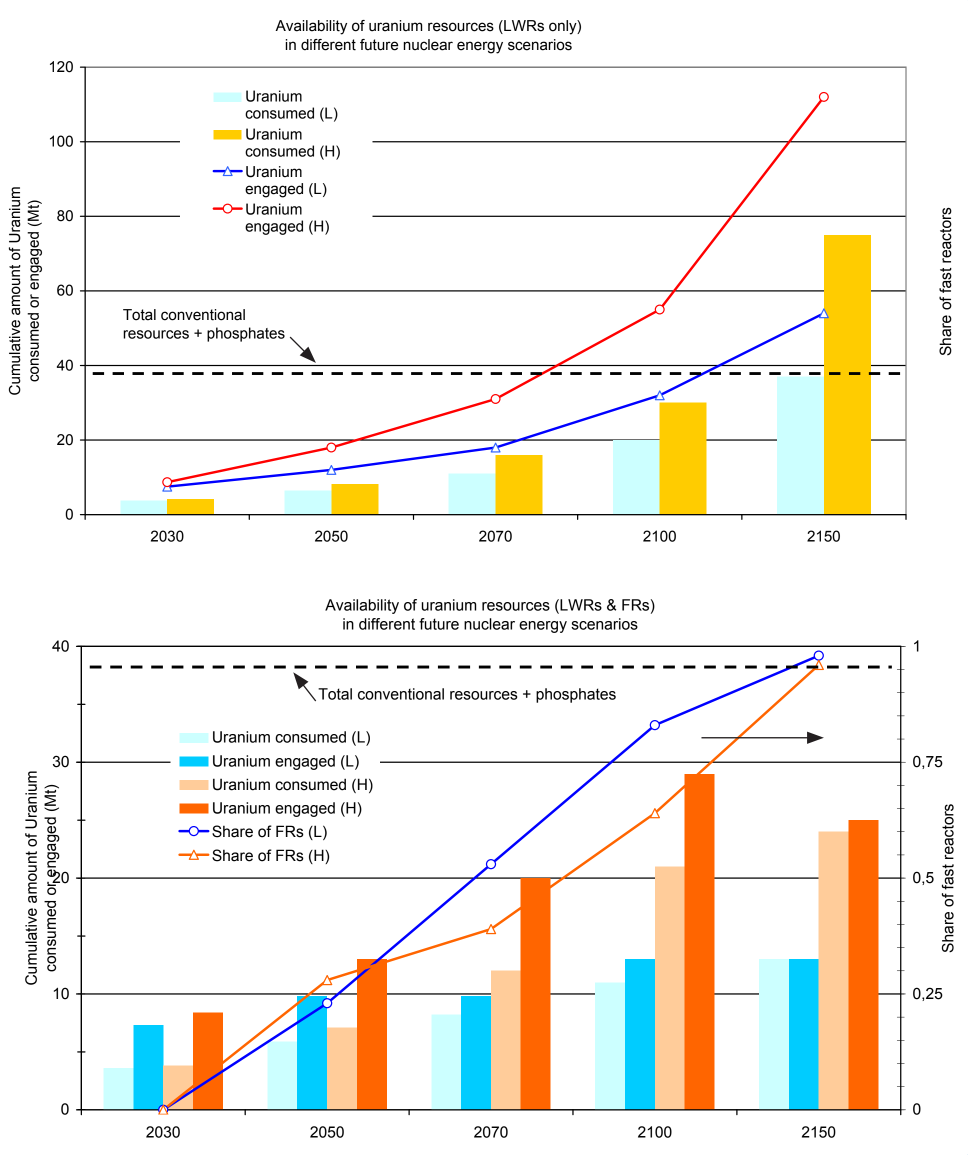

Figure 13. The amounts of uranium consumed and engaged in the high (H) and low (L) nuclear power production scenarios depicted in Figures 11 and12. Both open cycle (LWRs only) and closed fuel cycle (fast reactors and LWRs) are considered).

Industrial development of innovative technologies such as fast neutron reactors will not eliminate the requirement to introduce new LWRs due to plutonium availability in the spent fuel from LWRs. Therefore, third and fourth generation systems would coexist for a long time, maybe a century, especially if future energy requirements are high.

The need for uranium will remain high also during an "as-fast-as-feasible" transition period to fast reactors, but, owing to the introduction of fast reactors, could be limited to about 11 to 21 Mt by 2100 for the "natural uranium consumed" and less than 30 Mt for the "natural uranium engaged".

5. Waste management and disposal

The main objective of nuclear waste management is to protect human health and the environment, now and in the future, without imposing undue burdens on future generations. Repositories are already in operation for the disposal of low- and medium-level radioactive wastes in several countries. Deep geological repositories are the most extensively studied technical options for safe and long-term disposal of high-level radioactive waste. Worldwide, there are not yet repositories for high-level waste, and none are under construction either. Resolution of both technical and political/societal issues is still needed. Solutions to waste management and disposal are crucial for meeting sustainability goals for nuclear. Progress in gaining improved societal acceptance of the siting of these repositories has been recently achieved.

In Finland the waste management company, Posiva Oy, which is responsible for the disposal of spent nuclear fuel, filed in May 1999 an application to the Government for a Decision-in-Principle (DiP) on the construction of a final disposal facility. In May 2001, by a clear majority, the Finnish Parliament ratified the favourable DiP made by the Government in December 2000. The final disposal facility (Fig. 14) will be built at Olkiluoto, with the original DiP applying to the spent fuel from Finland's present four nuclear power plant units. In May 2002, in parallel with the decision on the fifth Finnish nuclear unit, the Parliament also ratified a new DiP on the final disposal of the spent nuclear fuel of the fifth reactor unit, Olkiluoto 3. Along with the plans to construct additional nuclear power plant units, there are environmental impact procedures and DiP processes underway to expand the capacity of the spent fuel disposal facility at Olkiluoto for additional reactor units that are planned to be constructed during the next decade or early 2020s.

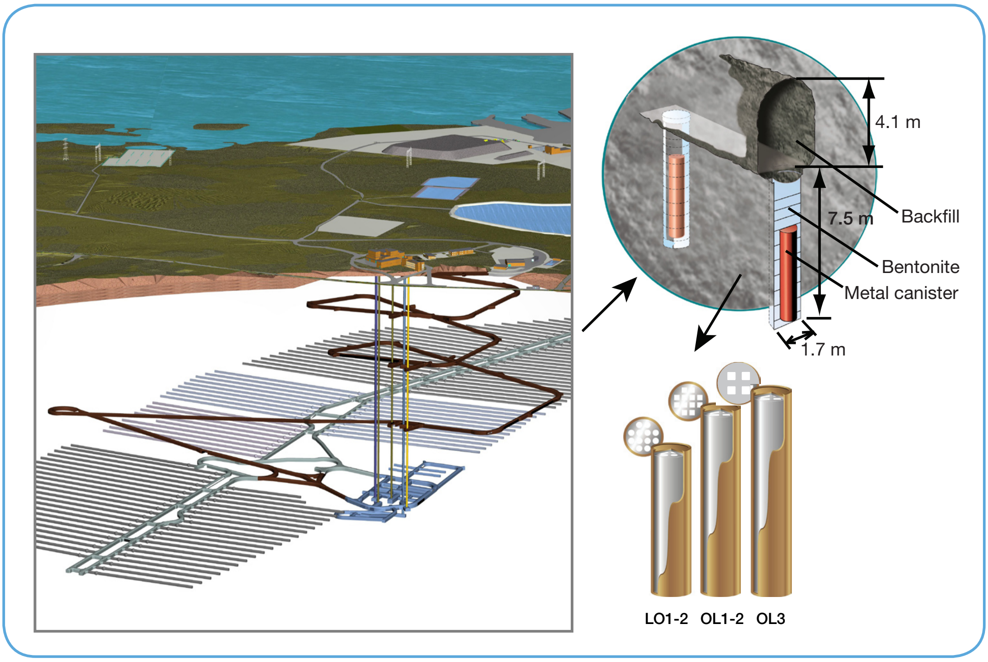

Figure 14. An animated photograph of the repository for spent nuclear fuel at Olkiluoto, Finland.

After detailed rock characterisation studies the construction of the encapsulation and disposal facility is expected to start around 2013, with commissioning planned for 2020.

Similarly, in Sweden a repository siting process is now concentrating on the comparison of site alternatives close to the Oskarshamn and Forsmark power plant sites. In the USA the Yucca Mountain area in the state of Nevada has been chosen as the preferred site for a repository of high-level waste (spent LWR fuel) and extensive site characterisation and design studies are underway, although not without significant local opposition. The Yucca Mountain repository is expected to begin accepting HLW by 2017 at the earliest.

France is also progressing on high-level waste disposal as the bill approved in 2006 declares deep geological disposal as the reference solution for high-level and long-lived radioactive wastes, and sets 2015 as the target date for licensing a repository and 2025 for opening it. The bill of 2006 also affirms the principle of reprocessing spent fuel and requires that the design should allow retrievability of waste packages from the repository. France further examines the possibility of transmutation of the long-lived actinides in fast neutron reactors to reduce the volume, heat load and radionuclide inventory of the ultimate HLW.

Annually, around 10,000 tonnes of heavy metal in the form of spent nuclear fuel is discharged from operating nuclear power reactors. The management of this spent fuel is an important factor influencing the future of nuclear energy, and deals with issues related to long-term interim storage and spent fuel treatment. Less than 20% of spent fuel is currently reprocessed. As the amount of spent fuel in storage climbs steadily, so does the need for efficient management of all issues related to the back-end management of spent fuel. Increased reliance on nuclear energy as a major contributor in mitigating the emissions of greenhouse gases requires in the long-term more efficient use of uranium resources. At the same time the reduced heat load and lower radionuclide inventories facilitate the design of repositories for geological disposal of high-level wastes.

6. Conclusions

Nuclear energy is a well-established source of electricity with minimal CO_2 production. It currently generates 16% of electricity worldwide. It is at its best in well-developed countries with stable political and economic conditions. In recent decades its development has been gradual and rather a small amount of new capacity has been built. At the moment, however, there seems to be new beginning, while some countries are still considering phase-out. The new start is mainly due to increased reliance on the technology, its estimated low and stable energy price and because it is practically CO_2 free. There is also more information on fuel waste management treatment, e.g. the Finnish and the Swedish solution. Also the fuel resources are estimated to be enough for about a hundred years with the current power generation and once-through fuel management.

The technology is challenging, and a lot of efforts from the vendors and operators are needed to maintain the good operational and safety records. Also, society continuously needs to invest in basic infrastructure, such as education. A strong regulator, a high safety culture among all the parties and efficient international co-operation are needed to maintain the current favourable situation. At the same time efficient international co-operation is needed to fight against the risk of proliferation. Also in this respect, new technologies or fuel choices could mitigate the threat.

Nuclear energy could make an even bigger contribution to curbing climate change if the next generation of technologies are eventually taken into use. They would bring fuel resources for much wider application for hundreds of years, and nuclear energy could also be used to produce energy carriers other than electricity. Such options are partly open already now, but to fully exploit the potential benefits of nuclear energy much more research and development efforts are needed, not to mention the political will.

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Role of fossil fuels in the future

Jouni Hämäläinen
Technology Manager

1. Global challenges and their implications for the energy sector

The main global drivers of the energy system are growth of energy demand due to increasing population and economic output and, on the other hand, challenges linked to energy security and mitigation of environmental impacts, especially climate change. It is estimated by the International Energy Agency (IEA) that global primary energy demand will increase by 50% between now and 2030, and over 70% of this increase will come from developing countries, especially from China and India. The increase in the use of energy has lead to considerable emissions of greenhouse gases, which are believed to warm the climate of the Earth and to cause remarkable damages to ecosystems and human settlements. The EU has proposed a target to limit the rise of the global average temperature to two degrees Celsius compared with the temperature of the preindustrial era. According to the latest assessment report of the Intergovernmental Panel on Climate Change (IPCC) the two-degree target requires that global emissions should be reduced at least by 50% by the middle of the century. For developed industrial countries, even much higher emission reductions can be expected.

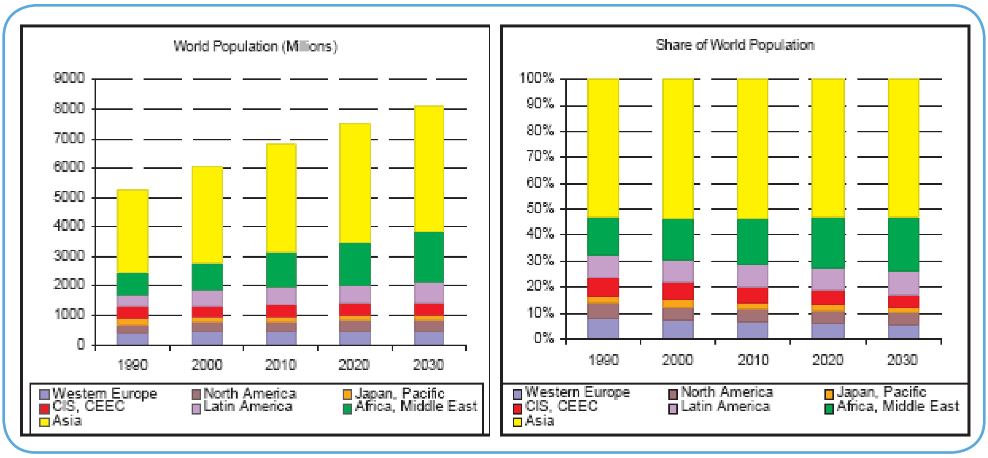


Figure 1. Development and share of world population (International Energy Outlook 2008).

According to current estimates, about half of the increase in global demand goes to power generation and one-fifth to meeting transport needs – mostly in the form of petroleum-based fuels. Fossil fuels are expected to remain the dominant source of primary energy, accounting for 84% of the overall increase in demand between 2005 and 2030. Renewables, such as wind and solar, and other abatement measures, such as improved energy efficiency, offer opportunities to reduce CO_2 emissions, but it is unlikely that these alone will enable the EU to reach its GHG abatement targets by 2030. By most accounts, additional measures will be required – such as Carbon Capture and Storage (CCS). In the energy spectrum as a whole, oil is expected to remain the single largest fuel, though its share in global demand will fall from 35% to 32%. In line with the spectacular growth of the past few years, coal will see the biggest increase in demand in absolute terms, jumping by 73% between 2005 and 2030 and pushing its share of total energy demand up from 25% to 28%. Most of the increase in coal use will arise in China and India. The share of natural gas will increase more modestly, from 21% to 22%. The fossil fuels will still have a predominant role in the world energy system in the coming decades.

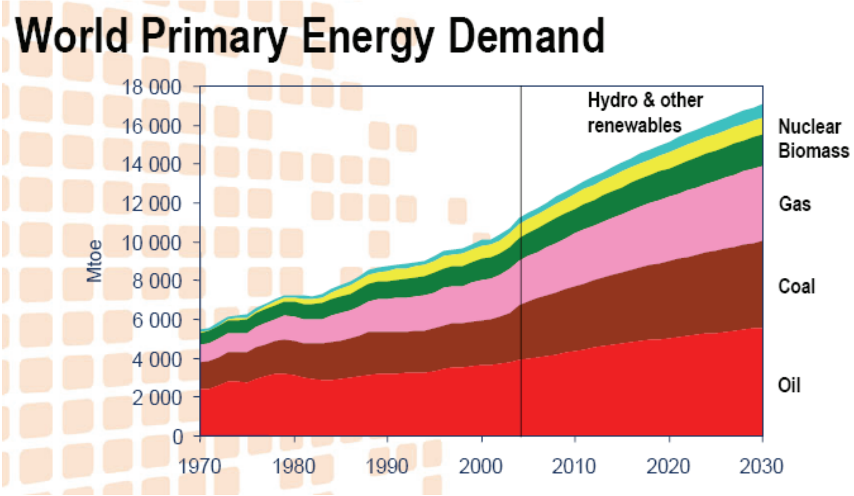


Figure 2. World primary energy demand until 2030. Global demand grows by more than half over the next quarter of a century, with coal use rising most in absolute terms. Fossil fuels will continue to dominate the energy mix, with oil, gas and coal together accounting for 83% of demand growth.

Ref. Coal in the IEA World Energy Outlook 2006. The Importance of Clean Coal Technologies in China, Brian Ricketts Coal Energy Analyst, IEA.

2. Electricity supply and generation in Europe

If the European energy system is considered, total net electricity generation in the European Union in 2006 was 3,200 TWh, accounting for almost one fifth of global electricity generation. Over half of the electricity is generated with fossil-fuel-fired plants. CO_2-free generation with wind, hydro and nuclear power accounted for 43 % of the total generation in 2006. Nuclear's share was 29 % (940 TWh). The largest nuclear-producing country in Europe is France with a generation of 430 TWh, almost half of the total nuclear power production in the EU27.

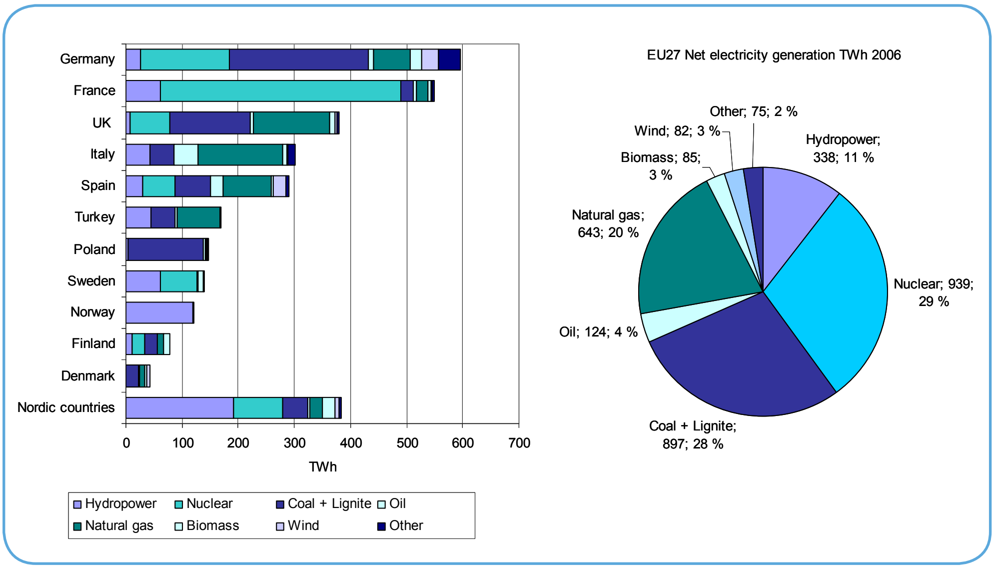


Figure 3. Electricity net generation in Europe in 2006 (Eurostat).

Europe's dependency on imported fossil fuels in power generation is about 25 % today, and the share is projected to grow as high as 40 % in the year 2030. The reasons for this growth are nuclear phase-out in some European countries and decreasing fossil fuel deposits in Europe. Also, the EU's climate strategies imply an increased use of natural gas, which is increasingly imported from non-EU countries.

3. Need for new capacity

Currently, the power plant capacity in Europe is quite old and there is an urgent need for new investments. A Green Paper published by European Commission in March 2006 stated that investments of around one thousand billion euros will be needed in Europe over the next 20 years to meet expected energy demand and to replace ageing infrastructure.

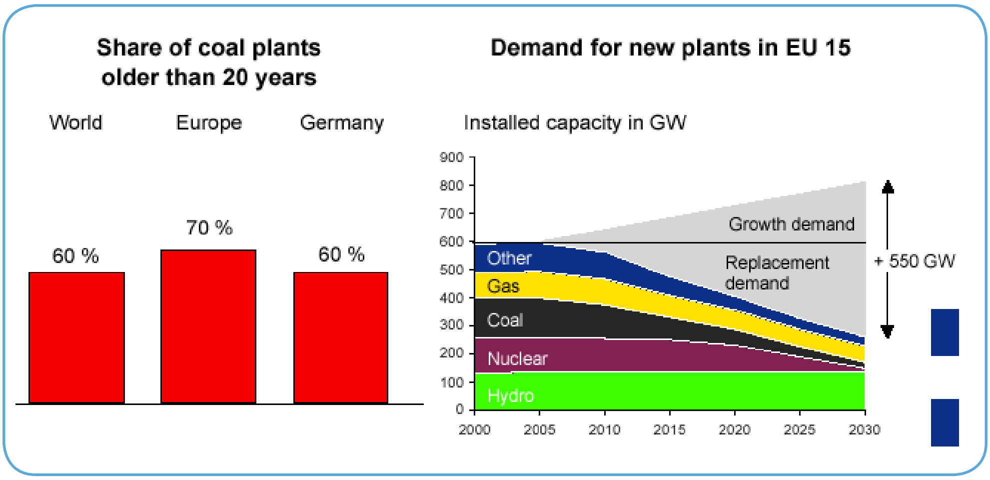


Figure 4. Need for new and replacement power generating capacity in the European Union (VGB PowerTech).

Obviously, the new investments will follow the needs for lower-CO_2-producing technologies such as renewables, nuclear power and clean fossil fuel technology.

The role of renewables will obviously be important, but it won't be enough to guarantee the total need for new energy investments. Germany, for instance, is currently investing in new coal power plants. Plants being invested in now will quite probably still be up and running in the year 2050. The role of nuclear power is also interesting since the phase-out of the nuclear power plants in both Germany and Sweden will have a tremendous effect on the electricity market. Germany produced 160 TWh of nuclear power in 2006; these power plants are going to be decommissioned by 2023. The share of fossil fuel in Germany will rise by 2020 as coal and gas plants will be used to replace a major part of the outgoing nuclear capacity. However, one very important driver for investing in new power capacity will be the environmental aspects, especially CO_2 emissions – therefore a wide spectrum of CO_2-free production as well as renewables will have an essential role in power generation in Europe.

4. How to reduce greenhouse gas emissions in power generation based on fossil fuels

Principally, there are three ways to reduce greenhouse gas emissions. First, one can substitute the use of fossil fuels by non-CO_2-producing sources like renewables or nuclear power. The second way of reducing emissions is to utilise technology with higher efficiency, i.e. to produce the same amount of energy with less fuel or to save the use of energy in end-use. The third option is to utilise so-called carbon capture technologies that are under development at the moment. The technologies where CO_2 is captured before being emitted to atmosphere are referred to as Carbon Capture and Storage (CCS).

5. Improving power generation efficiency and co-firing biomass together with coal

Increasing the efficiency of energy and power generation means using less fuel (and producing lower emissions) to produce the same capacity. There are on-going R&D projects that aim to reach over 50% efficiency with coal-fired units in power generation. Currently, the average efficiency of existing coal-fired units in Europe is slightly over 36%. By replacing the existing old units with modern available technology (efficiency ~45%), the same amount of electricity could be generated with 25% lower CO_2 emissions in Europe. This clearly shows the importance of improving the efficiency of power generation as there are several ongoing projects where the target is to reach a power generation efficiency above 50% (Thermie700 and Thermie Ultimo).

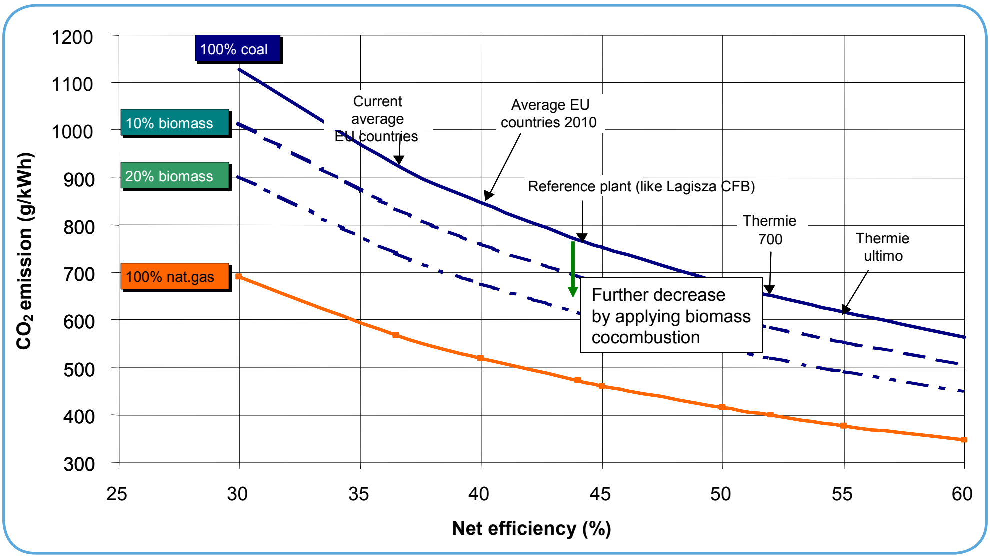


Figure 5. Decreasing CO_2 emissions by increased efficiency and by utilisation of non-CO_2 fuels like biomass (EC PowerClean Thematic Network, 2003, Fossil Fuel Power Generation in the European Research Area).

If fluidised bed combustion is considered – where Finnish industry has a leading position as a developer and supplier – the technology will give some extra benefit in terms of reduced CO_2 emissions thanks to its multifuel capability. Applying fluidised bed technology it is possible to produce heat and power from a few megawatts up to several hundreds of megawatts, depending on fuel supply security. In Finland we have good examples of full-scale operation. The largest scale boiler exists in the town of Pietarsaari. The boiler is the largest biofuel-fired CFB boiler (Circulating Fluidised Bed Boiler) in the world and was supplied with an output of 550 MWth. The boiler is designed to operate with both 100% coal and 100% biofuel. It is capable of burning the fuels in any given combination while staying within the emission limits.

The world's first supercritical CFB boiler is currently under construction at the Lagisza power plant at Poland. Total plant efficiency for power production will be in excess of 43%. Supercritical steam cuts fuel use per GWh of electricity generated by some 5% over conventional drum-based boilers. Due to its superior fuel flexibility, fluidised bed combustion offers the potential to reduce CO_2 emissions in power generation. Applying fluidised bed technology with a high efficiency and burning coal together with biomass, it is possible to achieve CO_2 emissions that correspond to even higher efficiencies. In the Lagisza case increasing the use of biomass by 10% would reduce nominal CO_2 emissions from 780 kg/MWh to 700 kg/MWh. However, scaling up the technology to the utility scale (600–800 MWe) with CO_2 capture readiness is still under development.

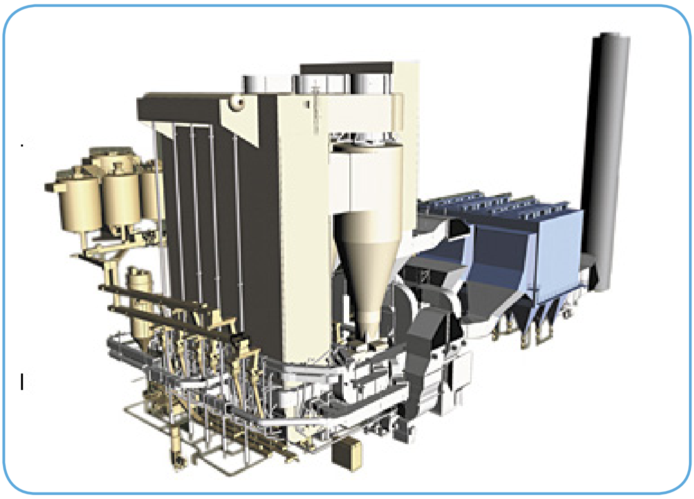


Figure 6. Schematic figure of the world's first once-through supercritical CFB boiler in Lagisza. Power production capacity 460 MWe (Foster Wheeler).

6. Carbon capture and storage (CCS)

Fossil fuels are expected to remain a significant source of the energy mix, comprising roughly 70 per cent of global and 60 per cent of European electricity generation up to 2030. However, this will necessitate a reduction in GHG emissions from fossil fuel power generation. Therefore, European industry has put a lot of effort into the development of CO_2 Capture and Storage (CCS) technologies in recent years. CCS is a group of technologies that aim to prevent the CO_2 generated by large stationary sources, such as coal-fired power plants, from entering the atmosphere. The technology aims to capture around 90 per cent of CO_2 emissions from these sources and permanently prevent their release into the atmosphere. The three principal capture processes available today work in different ways:

Oxy-fuel combustion: The fuel is burned with oxygen instead of air, producing a flue stream of CO_2 and water vapour without nitrogen. From this stream the CO_2 is relatively easily removed. The oxygen required for the combustion is extracted in situ, from air.

Post-combustion: CO_2 is removed from the exhaust gas through absorption by selective solvents.

Pre-combustion: the fuel is pre-treated and converted into a mix of CO_2 and hydrogen, from which CO_2 is separated. The hydrogen is then burned to produce electricity or fuel.

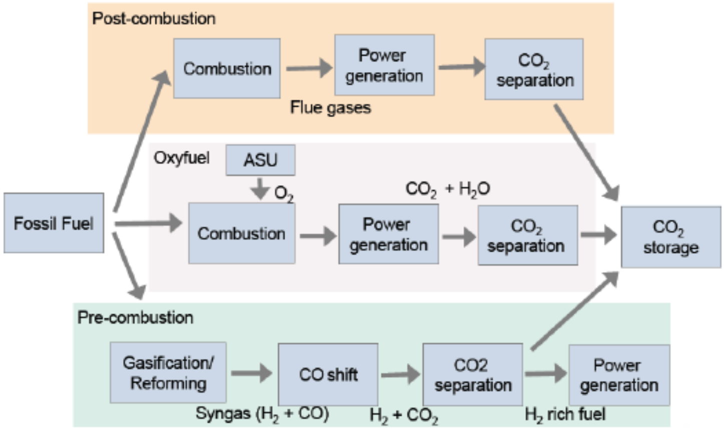


Figure 7. Options for Carbon Capture and Storage using fossil fuels (IPCC).

As seen above, CCS will need several additional steps or processes compared with a traditional plant, depending on the capture process.

7. Oxy-fuel combustion

One technology under development is oxy-fuel combustion, where the fuel is burned with a mixture of almost pure oxygen and recycled flue gas. An oxy-fuel power plant is therefore installed with an air separation unit (ASU) where the nitrogen is separated from the air, producing oxygen for the combustion process. Oxygen is mixed with recycled flue gases, which creates a mixture of primarily O_2 and CO_2 (as well as water) used as oxidants in combustion instead of air. By avoiding the diluting effect of nitrogen, the carbon dioxide capture from the flue gas becomes much easier and less power consuming. The composition of the flue gas depends on the flue gas recirculation ratio and consists mainly of CO_2, water vapour and O_2. Water, oxygen and other impurities can be removed from the captured CO_2 stream mainly by means of compression and cooling.

The oxy-fuel combustion plant therefore has two new units compared to a conventional power plant: an air separation unit (ASU) and a CO_2 processing unit (CPU). Both of these units increase the internal power consumption of the power plant, leading to a 7–12 percentage point decrease in the efficiency of electricity production. Integration and optimisation of the heat cycle of the power plant is therefore necessary to minimise the efficiency drop. This technology is currently in the demonstration phase and it is considered to be one of the most attractive technologies for future power plants with CCS. Oxy-fuel power plants could also be built as retrofits to existing power plants to reduce development costs and achieve early market entry.

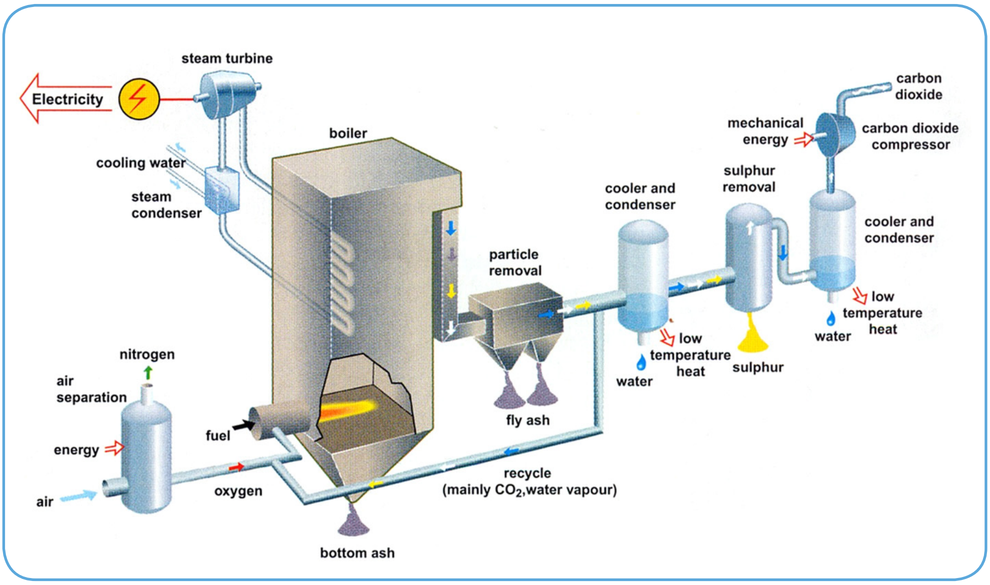
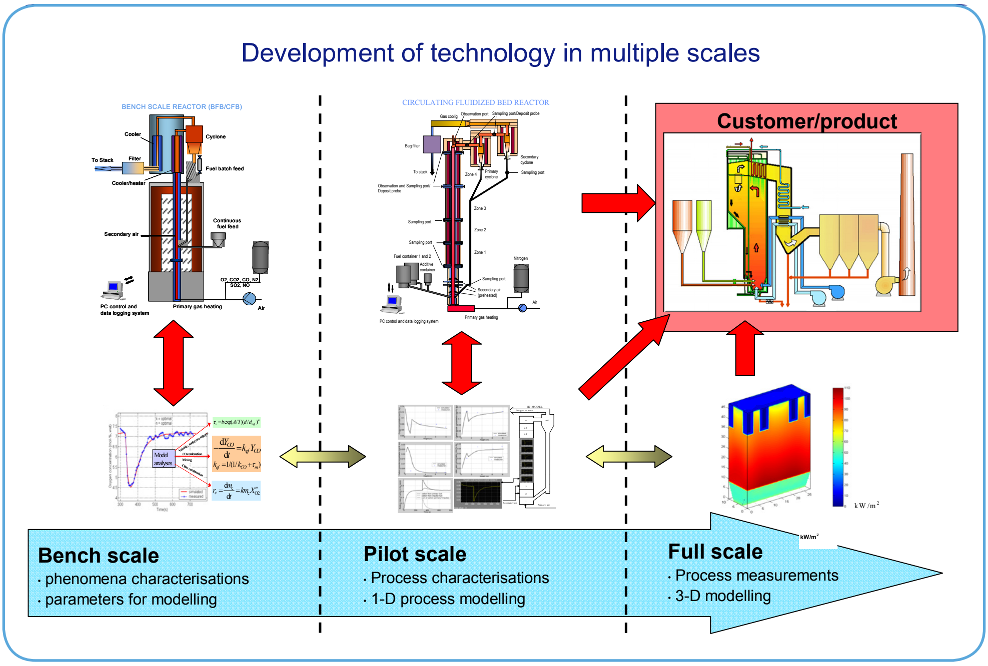


Figure 8. Schematic figure of an oxy-fuel combustion plant (Vattenfall).

Circulating fluidised bed technology (CFB) is proven to be feasible also in oxy-fuel concepts. Oxyfuel-related research has been varied at VTT during the last few years. VTT has unique laboratory-scale fluidised bed combustors that have been modified for oxy-fuel combustion research. VTT was one of the first in the world to successfully demonstrate oxy-fuel combustion in laboratory-scale conditions. As larger-scale oxyfuel and other CCS processes are planned and designed, the role of dynamic process analysis and behaviour will become necessary and important. VTT has the experience and capabilities to create the kind of simulation service that integrates knowledge of the process and the simulations tools that it has developed . Currently, studies on such a process-dynamics-related CCS concept have not been published. The new technology also creates new needs for materials. VTT has long-term experience in power plant material studies and we also have very good experimental resources to create an understand of material behaviour under CCS conditions in different processes.



Development of technology in multiple scales

Bench scale
- phenomena characterisations
- parameters for modelling

Pilot scale
- Process characterisations
- 1-D process modelling

Full scale
- Process measurements
- 3-D modelling

Figure 9. VTT's test facilities and modelling tools to study oxy-fuel combustion.

8. Post-combustion

In post-combustion capture, CO_2 is separated at low pressures from flue gases that generally have a CO_2 content of 3–15 vol-%. The most widely considered technology for post-combustion capture involves the use of chemical solvents, such as monoethanolamine (MEA), for absorbing CO_2 and producing a purified CO_2 gas stream suitable for compression and storage. For amine-based systems, the flue gas needs to be pre-treated to remove acidic components (NO_2 and SO_2 that otherwise would irreversibly degrade the solvent), after which it is cooled either in a heat exchanger or by direct contact with the amine in a scrubber column. The solvent absorbs the CO_2 in the flue gas, after which it is passed to a stripping column where it is heated in a reboiler to drive off the CO_2. After this regeneration, the amine is reused in the process.

The main advantage with post-combustion is that it is compatible with the majority of existing coal-fired power plants. However, the low partial pressure of CO_2 in the flue gas stream places high requirements on the solvent used for absorbing the CO_2. The heat requirements for regenerating the current generation of solvents are high, which impacts the overall efficiency of the power plant. The technology needed for post-combustion capture is already commercially available and in use to cover industrial CO_2 consumption, but would require scale up to 20-50 times that of current unit capacities for deployment in large-scale power plants in the 500 MWe capacity range for CCS purposes. For a power plant fitted with post-combustion capture, integration and optimisation of the heat cycle is necessary to minimise the efficiency drop.

The major drawback of solvent scrubbing is the cost due to the high energy requirements of the process. The energy required using MEA as a solvent can cause a 20% reduction in power generation for a pulverised fuel (pf) power plant. A reference example comes from the Ratcliffe power station in the UK. At present the thermal efficiency of this station is 38.9% (LHV). If the plant is retrofitted with Advanced Supercritical Boiler/Turbine (ASC BT) technology, the efficiency would rise to 44.9%. Further addition of an amine scrubbing CO_2 capture plant would reduce the efficiency to 35.5%. That is a reduction of 9.4 percentage points for a bituminous coal station. Although one of the advantages of amine scrubbing for post-combustion capture is that it can be retrofitted to some existing power plants in suitable locations, the difficulties in retrofitting post-combustion capture must not be underestimated. There is little point in retrofitting plants of low thermal efficiency since the efficiency losses would render the plant uneconomic.

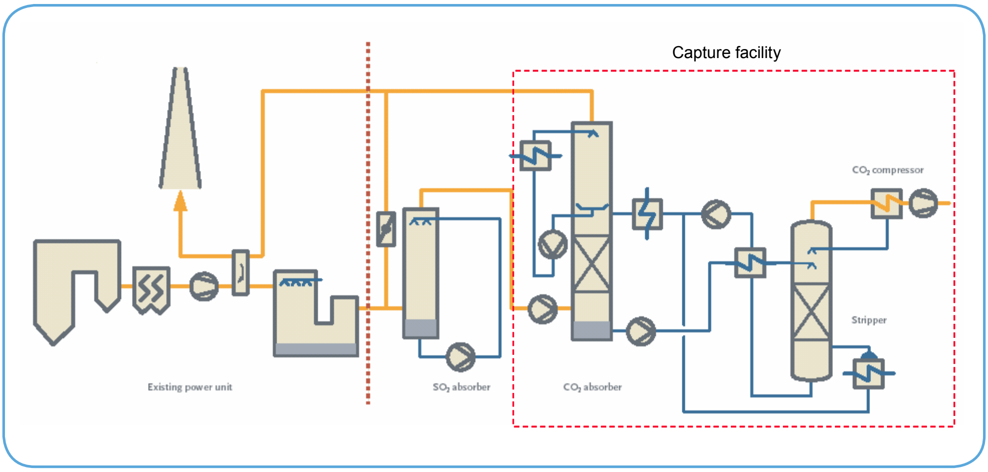


Figure 10. Post-combustion capture facility.

9. Pre-combustion

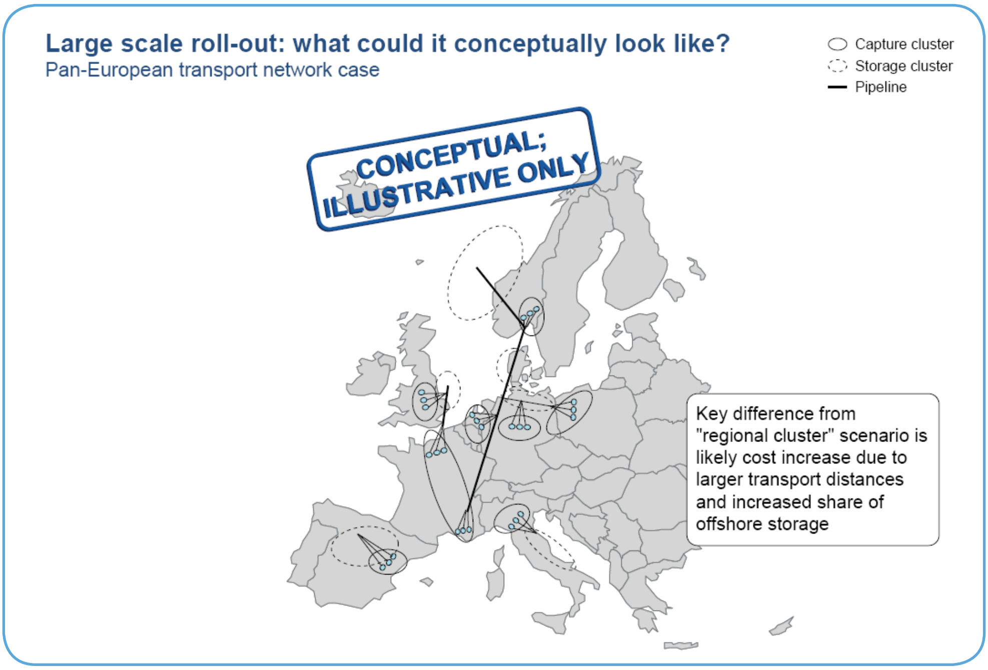
CO_2 can also be captured before combustion in fuel-burning power plants. Pre-combustion capture involves reacting a fuel with oxygen or air and/or steam to give mainly a synthesis gas composed of carbon monoxide and hydrogen. The carbon monoxide is reacted with steam in a catalytic reactor, called a shift converter, to give CO_2 and more hydrogen. CO_2 is then separated, usually by a physical or chemical absorption process, resulting in a hydrogen-rich fuel. The separated CO_2 is dried, compressed and stored, while the hydrogen-rich gas passes to a gas turbine to generate power. Pre-combustion would then be used at power plants that employ IGCC technology. The syngas must generally be cleaned to remove species such as sulphur, nitrogen (cyanides and ammonia) chlorides, and others that are either harmful to the equipment or the environment. Although the initial fuel conversion steps are more elaborate and costly than in post-combustion systems, the high concentrations of CO_2 (15–60 vol-%) in the syngas and the high pressures usually used in these systems are more favourable for CO_2 separation. Currently, the technology needed for pre-combustion capture is employed in large-scale production of hydrogen for industrial use. Since few gasification plants are currently in operation, pre-combustion capture could mainly be applied to new plants. Pre-combustion capture faces the same barriers to commercial application as gasification technology, including low availability, high requirements and high costs.

10. Transportation and storage of carbon dioxide

In order for CCS to be a useful option for reducing CO_2 emissions from power plants and industry, the captured CO_2 should be transported to a storage site, where it must be stored for a long period of time, at least thousands of years, in isolation from the atmosphere. The transportation to a storage site in most often needed since suitable storage facilities are seldom located near the CO_2 source. For large-scale CO_2 transportation, pipelines are the primary option, although shipping is also a possibility. Gaseous CO_2 is typically compressed for transportation to a pressure above 80 bar in order to avoid two-phase flow regimes and to increase the density of the CO_2, thereby making it easier and less costly to transport by pipeline. Ships or road and rail tankers are also technically feasible alternatives for the transportation of CO_2, but this currently takes place on a small scale because of limited demand. In these options, the pressure of the CO_2 in the insulated tanks is typically around 7–20 bar. The cost of pipeline transport is dependent on the flow rate, terrain, offshore/onshore transportation, and distance. For distances over 2,000 km, transportation by ship is typically cheaper than transportation by pipeline.

The regional distribution and cost of storage in Europe will probably play an important role. It has been shown in one scenario that, depending on the nature of storage, different kind of local/regional capture-storage clusters could be created in Europe. The abatement potential of these clusters would be 0.4 Gt of CO_2 per year in 2030 with 80 to 120 CCS sites.

According to another scenario a Pan-European network is one possibility if there is not enough accessible and public accepted local storage. In this case the solution could be offshore storage, meaning a Pan-European transport network connecting regional clusters. The longer transport distances involved in shifting to predominantly offshore storage could double transport and storage costs to about 18 € per tonne CO_2 for offshore versus about 9 € per tonne CO_2 for onshore storage in 2030. However, such a Pan-European network would involve significant regulatory and logistical challenges.



Large scale roll-out: what could it conceptually look like?

Pan-European transport network case

Key difference from "regional cluster" scenario is likely cost increase due to larger transport distances and increased share of offshore storage

Figure 11. Conceptual design of CO_2 capture clusters and transport network in Europe (McKinsey & Company).

Due to the large amounts of CO_2 that needs to be stored, only a handful of storage options can be considered. Currently, the only technology that has reached the demonstration stage for accomplishing CO_2 storage on a sufficiently large scale is the use of underground geological formations. Storage is possible, amongst other options, in various types of geological formations. The primary options are depleted oil and gas fields and natural underground formations containing salty water, known as deep saline aquifers.

Sedimentary basins (natural large-scale depressions in the Earth's crust that are filled with sediments) that are potentially suitable for CO_2 storage are distributed around globe, both onshore and offshore. The most promising formations are nearly depleted or depleted oil and gas reservoirs, deep saline formations, and unminable coal beds. In each case, CO_2 could be injected in compressed form into a rock formation at depths greater than 800 m, where the CO_2 is in a liquid or supercritical state because of the ambient pressures. To ensure that the CO_2 remains trapped underground, a well-sealed cap rock is needed over the selected storage reservoir. The geochemical trapping of CO_2 (i.e. fixation as carbonates) will eventually occur as CO_2 reacts with the fluids and host rock in the reservoir, but this happens on a time scale of hundreds to millions of years. In order to minimise the risk of CO_2 leakage, the storage sites must be monitored for a very long time. Currently, there are several projects running that demonstrate this technology.

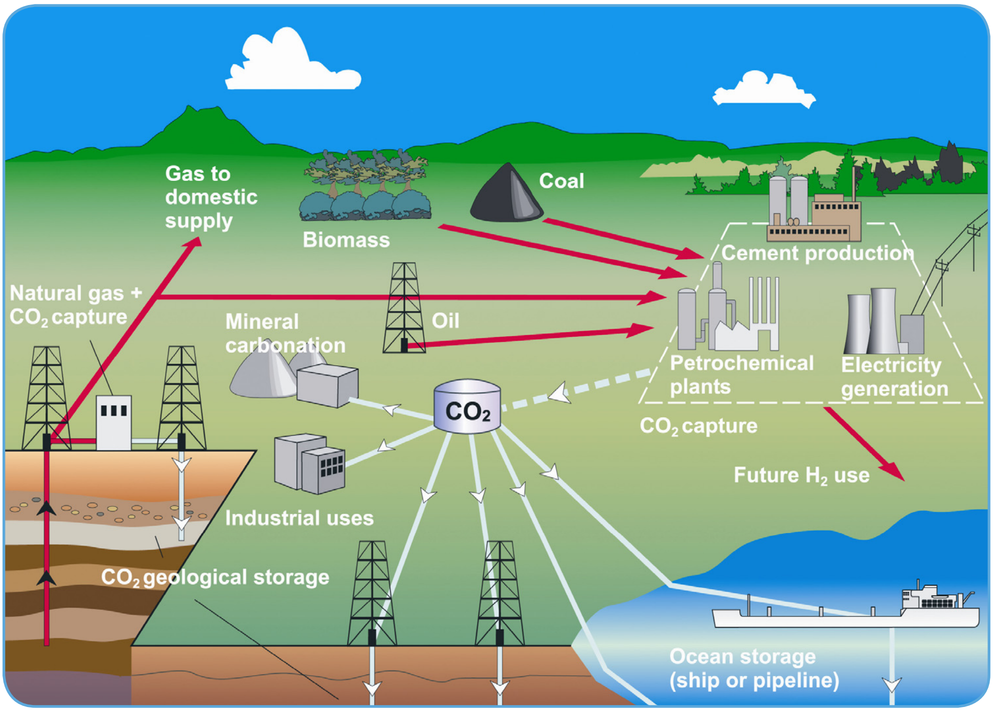


Figure 12. Alternatives for storage of CO_2 (IPCC 2005).

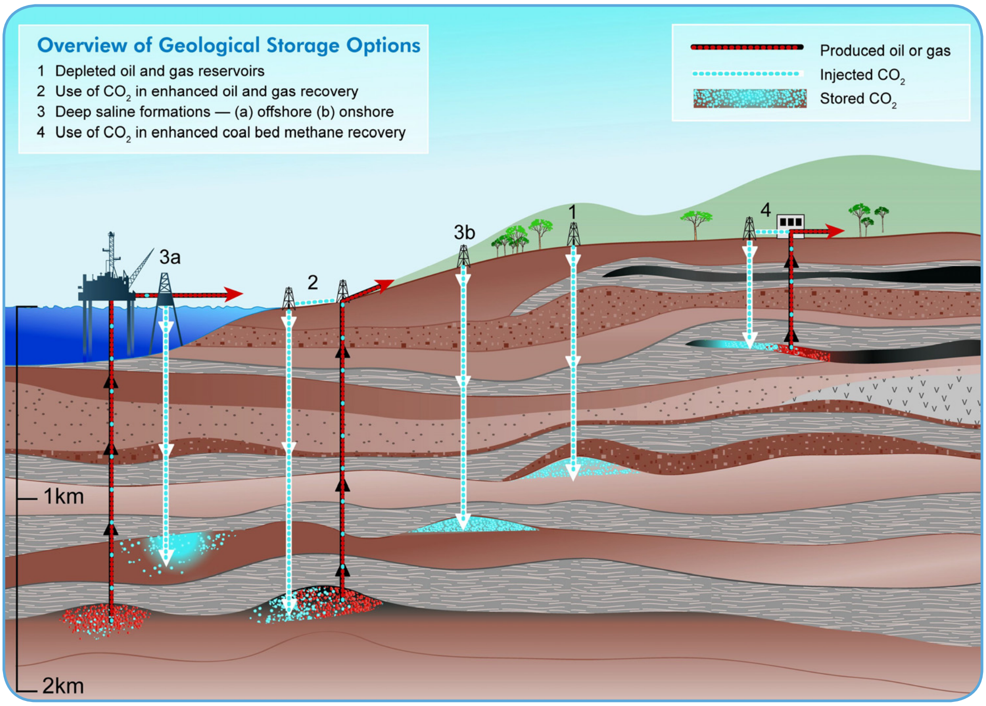


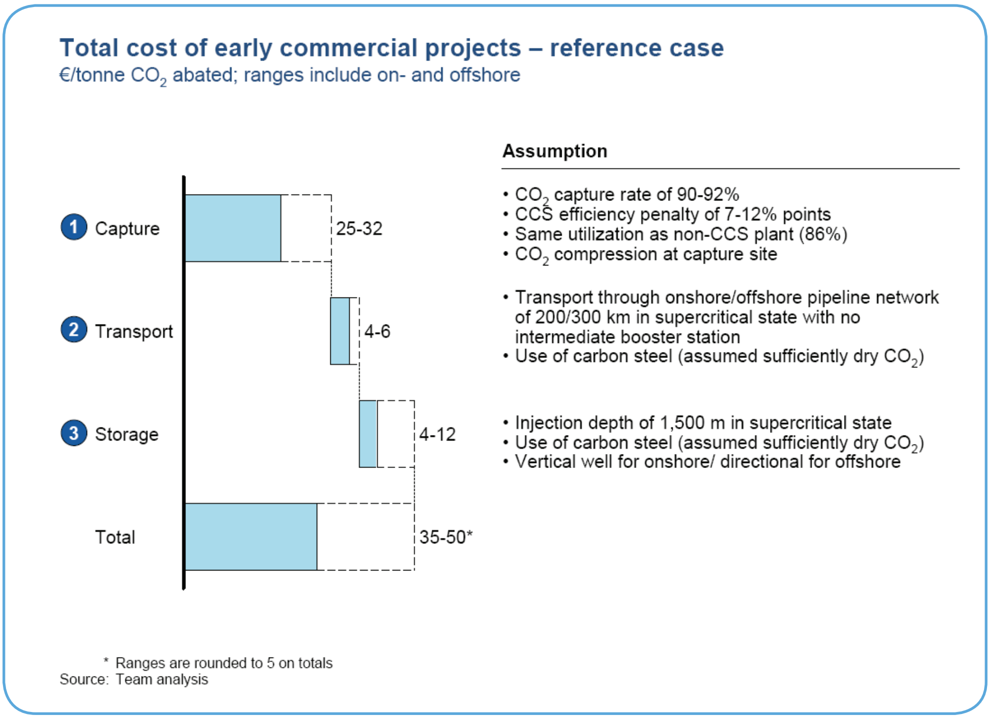
Figure 13. Underground storage alternatives (IPCC 2005).

11. Performance and cost estimates for CCS

The main energy requirements and costs of implementing CCS are related to the CO_2 capture step. All of the current main technologies for capturing CO_2 from power plants require both a significant amount of additional equipment and a significantly increased input of energy compared with power plants without CO_2 capture. In addition to the energy requirements of the separation technology used, the CO_2 must also be compressed for transportation to a secure storage site, as discussed above. The energy needed to capture 90% of the CO_2 from a power plant using the best current technology increases the fuel consumption per unit of produced electricity by 11–40% compared with power plants without capture. Therefore, CO_2 capture also increases the cost of electricity production by 35–85% (IPCC 2005). However, none of the main capture technologies are yet in operation at a full commercial scale.

This lack of operational experience means that there is a high degree of uncertainty regarding the cost of capture.

Anyway, future cost projections for CCS depend on which technologies are used, how they are applied, how much the costs will fall due to development and deployment, market uptake, and fuel prices. According to a recent report by McKinsey & Company (2008), CCS costs for early demonstration plants possibly deployed around 2012–2015 would typically be in the range of 60–90 €/t net CO_2 abated. When the first full commercial-scale CCS plants are built, possibly shortly after 2020, the cost were estimated to be 35–50 €/t net CO_2 abated. The costs can be broken down into 25–32 €/t net CO_2 captured and compressed (90% capture rate), 4–6 €/t net CO_2 transported (500 km) and 4–12 €/t net CO_2 stored (operation 40 years, monitoring for 40 years after closure). When the CCS market has matured (after 2030) the total costs are likely to go down to 30–45 €/t net CO_2 abated, which is in line with the expected carbon prices in that period. Abatement costs for non-power and retrofit CCS applications are estimated to be higher than those for new power plants with CSS. The actual costs are expected to vary significantly between individual projects, depending on scale, location and technology in use. In the future, power plants employing super alloys, high temperature hydrogen gas turbines, and new CO_2 separation technologies could enable power generation efficiencies with CO_2 capture that are comparable with current conventional plants without capture.



Total cost of early commercial projects – reference case

€/tonne CO_2 abated; ranges include on- and offshore

Assumption

- CO_2 capture rate of 90-92%
- CCS efficiency penalty of 7-12% points
- Same utilization as non-CCS plant (86%)
- CO_2 compression at capture site

- Transport through onshore/offshore pipeline network of 200/300 km in supercritical state with no intermediate booster station
- Use of carbon steel (assumed sufficiently dry CO_2)

- Injection depth of 1,500 m in supercritical state
- Use of carbon steel (assumed sufficiently dry CO_2)
- Vertical well for onshore/ directional for offshore

* Ranges are rounded to 5 on totals
Source: Team analysis

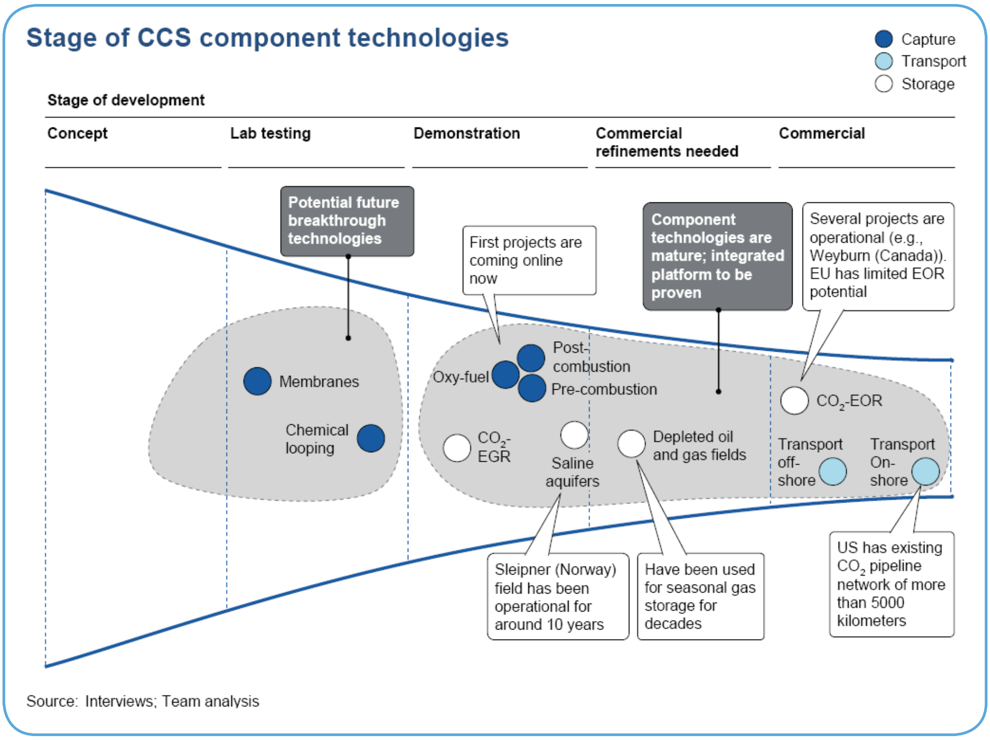
Figure 14. Analysis of CO_2 abatement costs in early commercial projects (McKinsey & Company).

12. Maturity and deployment of CCS

A number of international organisations have been initiated by the public and private sectors world-wide to study, develop and promote CCS technologies. In Europe, a program is being planned for supporting the construction of 12 demonstration plants implementing CCS. Recently (in September 2008), Vattenfall's 30 MW Schwarze Pumpe oxy-fuel pilot capture project in Germany was opened. Several other CCS projects have been announced recently, e.g. in Germany (RWE's Hürth project), the US (AEP Alstom Mountaineer), Australia (Callide Oxy-fuel) and China (GreenGen). Although CO_2 capture has not yet been applied on a full-scale (> 100 MW) power plant, it is intended that a total of 20 full-scale CCS projects for power generation will be initiated during the next decade.

Some technologies are extensively deployed in mature markets (e.g. injection of CO_2 into oil fields for enhanced oil recovery) while others are still in the research, development or demonstration phase. While current research in CCS focuses on reducing the costs for CO_2 capture processes, improving the monitoring and safety of geological storage is also of great interest.

Most of the planned European CCS projects are intending to use either oil fields or saline aquifers in the North Sea for CO_2 storage. Several projects are also being initiated in North America, Australia, and Asia. EOR is in fact necessary for continuing oil production from depleting oil fields in several regions of the world.



Source: Interviews; Team analysis

Figure 15. Stages of development of different CCS components. Source McKinsey & Company.

13. CCS abatement potential

According to the predicted increase in electricity demand, fossil-fuel-based electricity generation is expected to double globally by 2030. The single largest fossil fuel in the energy mix is coal, at 40 per cent of the global energy mix in 2005, forecast to increase to 45 per cent by 2030. Today CCS is the only technology known to be able to capture emissions from existing CO_2 emitters.

Various recent reports estimate that CCS could potentially abate between 1.4 and 4 Gt globally by 2030 (e.g. Stern 1.4 Gt, IEA 4 Gt, and McKinsey/Vattenfall 3.5 Gt). McKinsey and Vattenfall's global cost curve work estimates that up to 3.5 Gt per year of abatement could be achieved from CCS globally 0.4 Gt of it in Europe.

CCS requires long lead times before it can be deployed at full scale. In 2007, only four large-scale CO_2 storage projects were in operation around the world, each injecting over 0.5 Mt of CO_2 annually. In order to accelerate the pace of the technology development, international co-operation and sharing of best practices is required. In addition to technology, also legal guidelines, regulatory frameworks, risk management procedures, and international market mechanisms must be developed. It also requires large investments in single projects. The corresponding CO_2 abatement of each single plant is large: one CCS power plant could provide roughly 1.5 million European households with low-carbon electricity. By comparison, providing the same number of households with wind power would require roughly 1,400 typical full-scale (2.3 MW) wind turbines.

CCS has an added attraction: it reduces emissions from reliable "base-load" power (power that can run 24 hours a day, 365 days a year). Today, nuclear and coal typically fuel base-load plants in Europe, and eliminating coal from the power mix, as might be called for without CCS, would have significant implications for the power system. This would potentially put European energy security at risk: while well-supplied with coal, Europe is short of oil and gas.

14. Summary

The growth of energy demand due to increasing population and economic output will increase in the future. The International Energy Agency (IEA) estimates that global primary energy demand will increase by 50% between now and 2030, and over 70% of this increase will come from developing countries, especially China and India. The increased use of energy has led to considerable emissions of greenhouse gas emissions, and many countries have proposed a target to limit the rise of the global average temperature to two degrees Celsius compared with the temperature of the preindustrial era. According to the IPCC, this means reducing global emissions by at least 50% by the middle of the century.

On the other hand, the availability of and demand for energy probably means that fossil fuels will continue to play a key role in the energy mixture of the future. Naturally, the challenge is to reduce dramatically the greenhouse gas emissions of power generation based on fossil fuels, but there are several options available and CCS technologies are under development and demonstration. CCS processes need additional process phases compared with traditional power plants, which brings a penalty in power generation efficiency of 11–40% compared with power plants without CO_2 capture. Additional costs will also come from transportation and storage of CO_2. The final costs are, however, dependent on individual projects, scale, location and technology in use.

The deployment of CCS technologies is progressing very quickly at the moment. Several demonstration projects are running and there are plans for many new ones. Achieving CCS on a full commercial scale will require the construction of a huge infrastructure encompassing a CO_2 transport network and large-scale storage solutions. Full-scale deployment will therefore take a long time to accomplish. On the other hand, CCS will enable the utilisation of enormous fossil fuel resources with low CO_2 emissions and will guarantee clean power production to meet the needs of increasing energy demand.

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Bioenergy and other renewable energy sources as a means to reduce emissions

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1. Role of biomass as a renewable energy source

Biomass currently accounts for approximately 14% of the world's final energy consumption. About 25% of its use is in industrialised countries, while the other 75% is in developing countries. At present, the use of biomass as a traditional fuel is about 38 ± 10 EJ per annum, and as modern energy, such as fuel and electricity, about 7 EJ per annum.

The IPCC, International Panel on Climate Change, released its Fourth Assessment Report in May 2007. The report estimated the available biomass energy resources to be 250 EJ per annum. The previous assessment report, released in 2001, gave a significantly higher estimate (441 EJ per annum) for biomass potential. VTT's estimate of global biomass resources up until 2050, 83 EJ per annum (Table 1), is more moderate than most of the other estimations. Nevertheless, it shows that the present use could be doubled. Agricultural and forestry residues and waste were estimated to be the most cost-competitive types of biomass.

The major reason for the differences in the potentials is that the two most crucial parameters – available land area for energy crops and their annual yield – have been given very different estimates. The availability of the land area depends on the demand of the agricultural area for food and feed production, an the yield depends especially on fertilisation, irrigation and available new species of high productivity.

Table 1. Biomass energy potential (EJ per annum) in different regions of the world by 2050 estimated by VTT. Published in IEA Technology Perspectives 2008.

Region	Bark EJ	Sawdust EJ	Forest residue EJ	Black liquor EJ	Bagasse EJ	Rice husk EJ	Straw EJ	Field crops EJ	Waste EJ	Firewood EJ	Total EJ
Africa	0.05	0.05	0.14		0.67	0.01	2.80	3.50	0.18	4.96	**12.37**
Australia and New Zealand	0.04	0.01	0.10		0.27		0.72	0.88	0.03	0.06	**2.10**
Canada	0.16	0.13	0.41				0.66	0.41	0.03	0.02	**1.83**
Middle and South America	0.13	0.05	0.33		4.10	0.09	1.70	2.13	0.28	1.89	**10.69**
China	0.08	0.01	0.2		0.66	0.65	2.05	2.57	0.93	1.56	**8.72**
Eastern Europe	0.07	0.02	0.17				0.65	0.81	0.14	0.15	**2.02**
Former Soviet Union	0.13	0.05	0.34				2.93	3.66	0.19	0.49	**7.77**
India	0.02	0.02	0.04		1.70	0.46	2.30	2.88	0.50	2.46	**10.38**
Japan	0.01	0.01	0.03		0.01	0.04	0.06	0.08	0.19		**0.44**
Middle East	0.01	0.01	0.03				0.80	0.50	0.16	0.05	**1.55**
Mexico	0.01		0.02		0.32		0.36	0.45	0.07	0.31	**1.53**
South Korea						0.03	0.02	0.03	0.05	0.02	**0.16**
USA	0.34	0.18	0.87		0.19	0.04	2.50	3.13	0.47	0.35	**8.07**
Western Europe	0.20	0.11	0.52			0.01	1.08	1.28	0.50	0.27	**3.98**
Other Asia	0.07		0.18		1.51	0.78	1.59	1.99	0.44	2.33	**8.89**
Total	**1.31**	**0.66**	**3.39**	**2.33**	**9.44**	**2.10**	**20.23**	**24.29**	**4.15**	**14.94**	**82.83**

2. Bioenergy – dominating renewable energy in Finland

In 2006, renewable sources produced 356 PJ (99 TWh) of energy, which was 24 per cent of the total energy in Finland. The share of bioenergy was 313 PJ (87 TWh), which covers nearly 90% of the renewables. Measured as final energy, renewable sources produced 335 PJ (93 TWh), or 30 per cent of final energy consumption. The share of renewable energy has increased steadily since the 1980s. The major users of solid bioenergy in the EU are France, Germany, Sweden, Finland and Poland (Fig.1). Finland is clearly the forerunner on the basis of bioenergy per capita (Fig.2). The role of non-solid biomass was still very limited in 2007.

Renewable energy – hydropower, bioenergy and wind – generated 25 per cent of Finland’s electricity in 2006. Biomass produced more than 10 per cent, a world record, and the amount was the highest in the EU (Fig. 3). Electricity is generated at about 100 power plants utilising varying biomass-based fuels and production technologies.

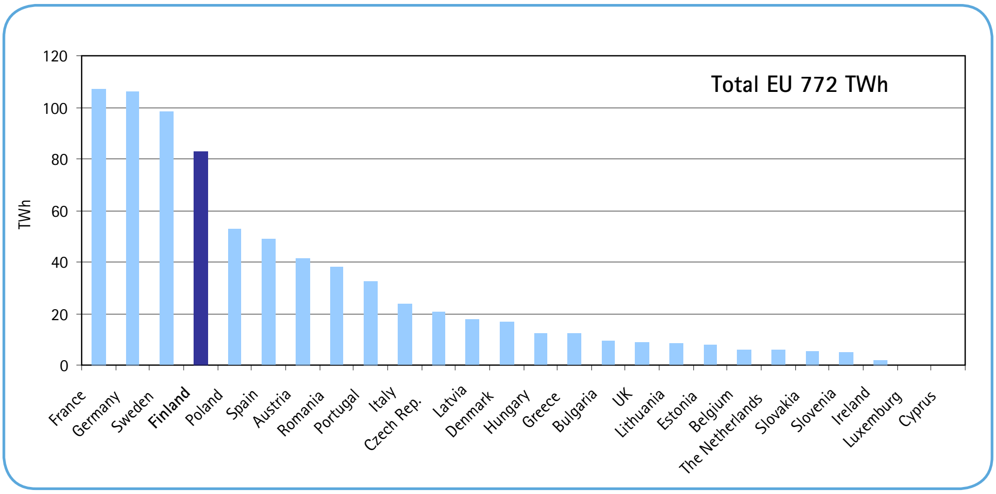

Figure 1. Primary energy from solid biomass in 2007 in the European Union. Source EurObserv'ER2008.

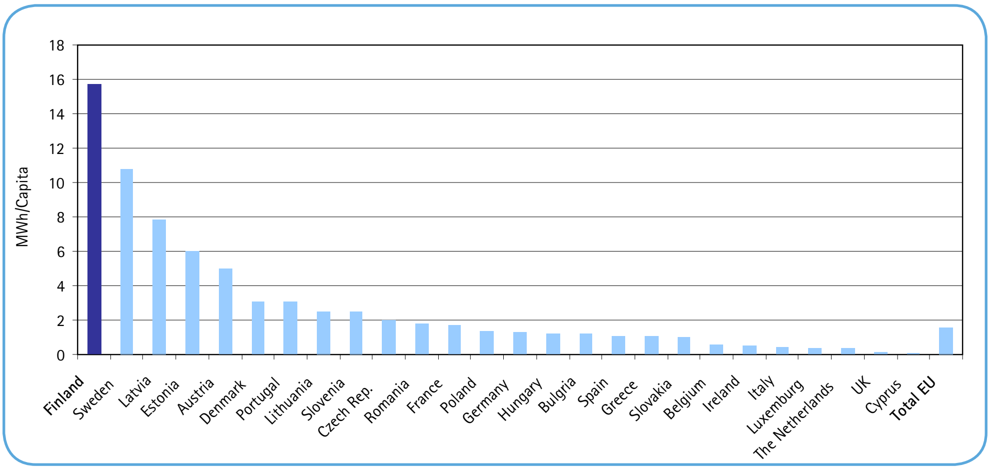

Figure 2. Primary energy from solid biomass per capita in 2007 in the European Union. Source EurObserv'ER2008.

The electricity is mainly generated by burning forest biomass composed of residues from pulp and paper production and forest chips in combined heat and power (CHP) plants. The biomass plants produce from 1 MW to 240 MW of electricity. The efficiency of biomass usage is exceptionally high in Finland because of the large share of CHP production. Nearly one third of Finland's electricity is produced in CHP plants, half of them in industry and another half in municipalities. Increased use of biomass can replace the use of fossil fuels in CHP plants partially or totally.

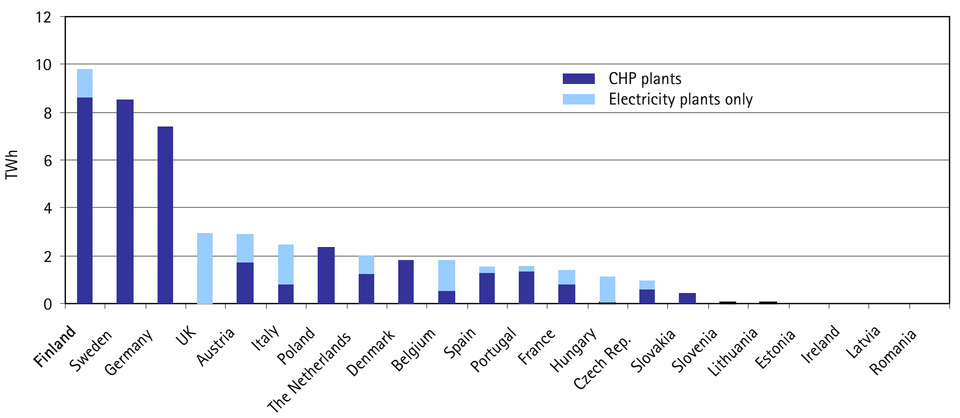

Figure 3. Electricity production from solid biomass by CHP and electricity-only plants in the European Union in 2007.

3. Challenging targets for the future

The proposed renewable energy target for Finland by 2020 is 38 per cent of final energy consumption. The Finnish Government has prepared a new strategy for long-term climate and energy policy. It is intended to stabilise final energy consumption at the present level by 2020, while increasing the use of renewable energy by 36 TWh. Bioenergy, wind and heat pumps are estimated to have the greatest potential.

The required share of renewable energy for the whole EU, 20% of final consumption, means the increase in renewable energy should be more than 1000 TWh.

4. Cost-effective incentives to promote renewable energy

The adoption of highly efficient, sophisticated technology has been the most dependable way of increasing the use of bioenergy in Finland. On the other hand, financial incentives have been established as crucial for the development, demonstration and deployment of new technologies. However, the new, more demanding targets for greenhouse gas reduction and renewable energy by 2020 require extra incentives.

Finland was the first country to impose a carbon-based environmental tax in 1990 by introducing a CO_2 tax on fossil fuels. Fossil fuels for heat production are taxed according to their carbon content.

Regarding electricity, the tax is levied on electricity generated or consumed and not on the fossil fuels used to generate it. A subsidy for electricity produced by renewable energy was introduced in 1997. Companies are not entitled to deduct the carbon or energy tax, but they pay a lower electricity tax than private consumers and the public sector.

Investment in renewable energy plant is co-financed by the government with grants of up to 40 per cent. The highest investment subsidies are allocated to cover the risks and higher construction costs of plants that demonstrate the use of new technologies.

Information dissemination and training have shown good results when deploying new energy technologies, especially when a large number of new stakeholders are involved.

5. Major biomass resources and end-users

In Finland biomass residues from forestry, agriculture, forest and food products, and biogenic waste are the most significant bioenergy sources, provided that they have no use as raw material or cannot be recycled. The utilisation of bioenergy could be increased by 50 per cent using indigenous biomass resources over the next ten years. Bioenergy would then exceed 30 per cent of primary energy consumption. These sources have turned out to be inadequate compared to the demand in the longer term. Dedicated energy crops and alternatively imports will then be required to meet fast-growing needs.

Finland is planning a significant increase in the share of bioenergy in residential and industrial heating, in district heating, in electricity production mainly at the CHP plants and in transportation. By 2050, bioenergy has the potential to become the market leader in the heating sector, the main source of renewable electricity and to provide a significant share of fuels used in transport.

6. Integration is the key to competitive bioenergy systems

Sustainability together with integration is evidently the basis for viable bioenergy systems. With integration it is possible to reduce investment and operational costs and gain adequate economies of scale. There are good examples of this: integration of the procurement of forest fuels with the procurement of forest industry feedstock has produced excellent results (Fig. 4). There is similar potential in the procurement of agricultural crops.

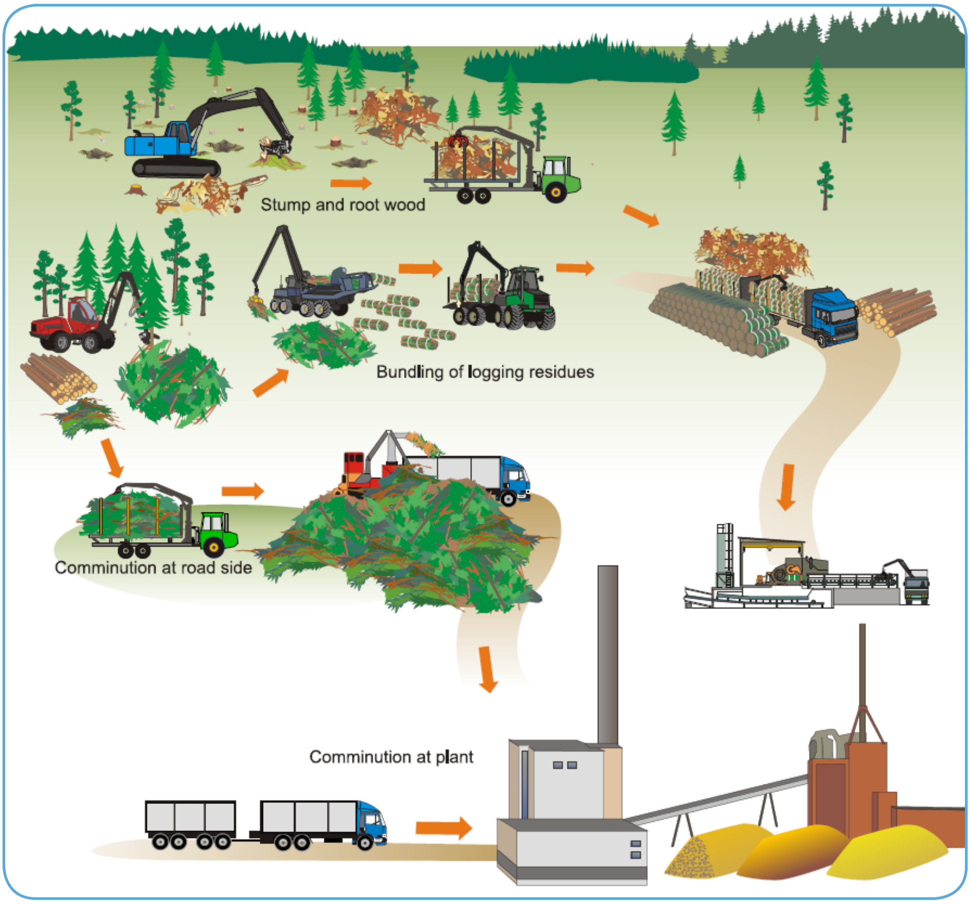

Figure 4. Wood procurement chain from forest to the plant.

Several sorts of biomass-based fuel can be co-fired with coal or peat: co-firing enables larger capacities and high efficiencies with low specific investment costs. Traditionally, in many applications, industry's need for process steam and municipal needs for district heat have been solved by CHP production.

Significant synergetic benefits are foreseen in biorefineries that will be able to produce simultaneously several bioproducts and energy products, such as heat, electricity, pellets or briquettes, bio-oils for heating and liquid biofuels for transportation, or synthetic natural gas suitable for the natural gas network or for industrial processes (Fig. 5).

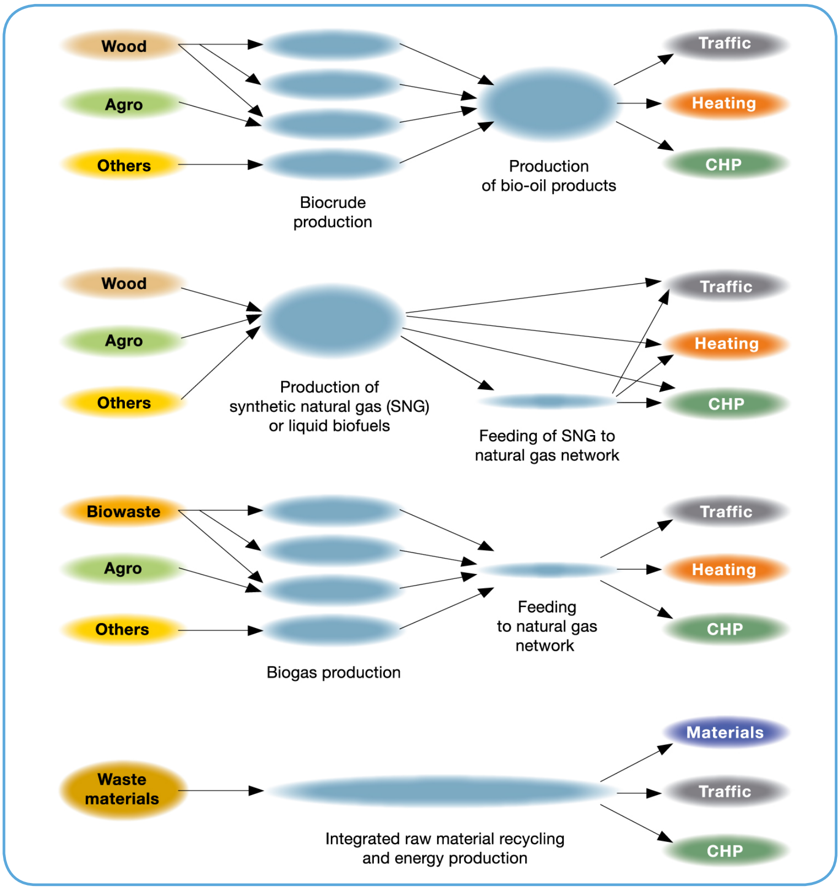

Figure 5. Options for the integrated use of several feedstocks (Growing Power, Tekes 2008).

7. Functional fuel market for biomass essential

A functional fuel market needs several independent suppliers; open information about prices; defined standards and norms for fuel quality; fixed terms of delivery; and reserve supply. The same requirements apply to biomass as a fuel. Finland has a long tradition of using peat as a fuel, and the practices that have evolved in trading peat can be applied to wood fuels, short rotation crops and recovered fuels.

Seasonal and annual variations in quality and availability are typical for forest fuels and short rotation crops. Also the volume of residues and by-products can fluctuate (Fig. 6). Ensuring that power plants can use a variety of fuels has proved to be the best guarantee of competitive fuel supply. Biomass requires local operations in production, harvesting and logistics, but geographical variations in demand and supply can be counterbalanced by more networking and organisational efficiency.

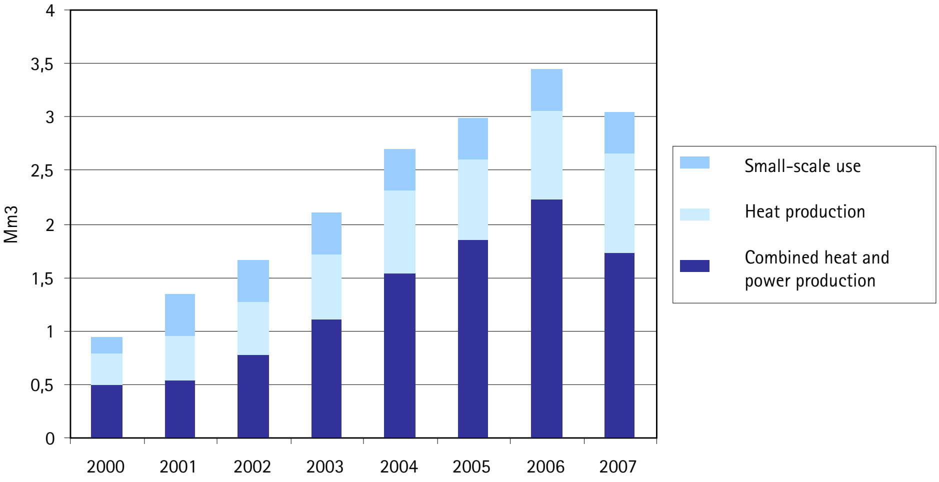

Figure 6. The use of forest chips in Finland in 2000–2007 (Growing Power, 2008).

8. More biomass from forests and fields

The potential biomass resources from agriculture, forests and industrial processes are ample, but the costs of biomass at the plant are hindering the increased use of biomass. The efficiency of the biomass procurement system is highly dependent on the environment and infrastructure in which it is operating. In addition, economic, social, ecological, industrial and educational factors, as well as local traditions, have an effect on efficiency. Every link in the production chain has to be optimised to improve profitability without compromising quality and supply security.

New silvicultural methods that can greatly increase biomass growth are being developed for Nordic forests. By optimising planting densities and time of thinning, and by increasing fertilisation, more biomass can be harvested per forest hectare without losses in biodiversity when the guidelines for sustainable forestry are followed.

It would be ideal if branches, tops and stumps for bioenergy were harvested at the same time as the felling of stem wood for forest products. The combined operations need new machinery and equipment. In future, mechanised thinnings and final cuttings will be followed by mechanised planting, even when conditions are difficult.

Projects to select and develop new energy crops for Nordic conditions have been implemented in the last few years. Reed canary grass has been shown to be a very viable plant that could be utilised as a fibre source. Promising new species have been found, for instance within knapweeds. Cut-away peatlands are fertile ground for the cultivation of energy crops.

There are plans to use algae and bacteria for energy purposes. Concepts for using flue gases or process waste waters as nutrients for algae and bacteria are at an early research phase.

9. More electricity compared to heat load

Fluidised bed technology has been dominant in large CHP plants using solid biomass (over 5 MW_e) since 1980s. The largest plants are designed for 165 bar/545 °C, and in the near future supercritical values will be introduced to fluidised bed boilers. Future improvements in the technology will focus on higher steam values and lower emissions from inferior biomass. The improved solutions will concentrate on new bed materials, new construction designs and materials for superheaters, and combustion conditions that are measured and controlled continuously. Fuel drying and production of fast pyrolysis oil could be integrated with the fluidised bed boilers via circulation of bed material.

The annual fuel consumption of large CHP plants is several TWh (or 10–20 PJ), which, in most cases, requires the co-firing of biomass and fossil fuels. Fluidised bed boilers allow co-firing of coal and biomass with low emissions. Once-through boilers should be developed to the highest capacity ranges, which would increase power output significantly. The development of oxyfuel combustion with CO_2 removal could enable negative emissions from the biomass combustion.

The development of thermal gasification and catalytic gas cleaning processes has been selected as one of Finland's research focuses. Both fixed and fluidised bed gasifiers are being improved to reduce tar and other harmful components when low-quality biomass feedstock, such as forest and agricultural residues, are burnt. Atmospheric gasifiers have been connected to existing boilers so that significant amounts of different biomasses can be co-fired. Gasifiers with sophisticated catalytic gas cleaning can provide syngas to combustion engines or gas turbines and, in the future, to fuel cells.

10. Second-generation biofuels are needed for the transportation sector

In Finland, the promotion of biofuels and other renewable fuels for transport is focused on the development of second-generation biofuel production technologies. The integration of biofuel production into pulp and paper mills is typical of the novel process concepts under development. These solutions do not disrupt food and feed markets. It is believed that second-generation biofuels can be produced more cost-effectively than current commercial biofuels. By using second-generation biofuels, it would also be possible to achieve significant reductions in greenhouse gas emissions. Agricultural crop resources are limited and new raw materials will be needed to meet the ambitious targets set in Europe and elsewhere. Wood-based biomass, by-products of the forest or food industries, or dedicated energy plants, will increase the biomass supply.

11. Several commercial demonstrations plants are planned

Research, development and demonstration projects are ongoing to introduce new second-generation biofuels to the market. The oil company Neste Oil and the pulp and paper company Stora Enso are together building a demonstration plant at Stora Enso's Varkaus mill. In the demonstration plant gasification of biomass, gas cleaning and the Fischer-Tropsch synthesis will be demonstrated, starting in early 2009.

The forest industry company, UPM, has announced that it will focus strongly on second-generation biofuels. UPM is co-operating with Andritz and its associated company Carbona on the development of technology for biomass gasification and synthetic gas cleaning. The diverse bioenergy company Vapo is looking for new business opportunities in the production of Fischer-Tropsch diesel from peat and wood.

Also, several new ethanol and energy production concepts that utilise commercial and industrial residues are being developed and will be demonstrated in the near future by UPM, L&T, St1 (Figure 7) and others.

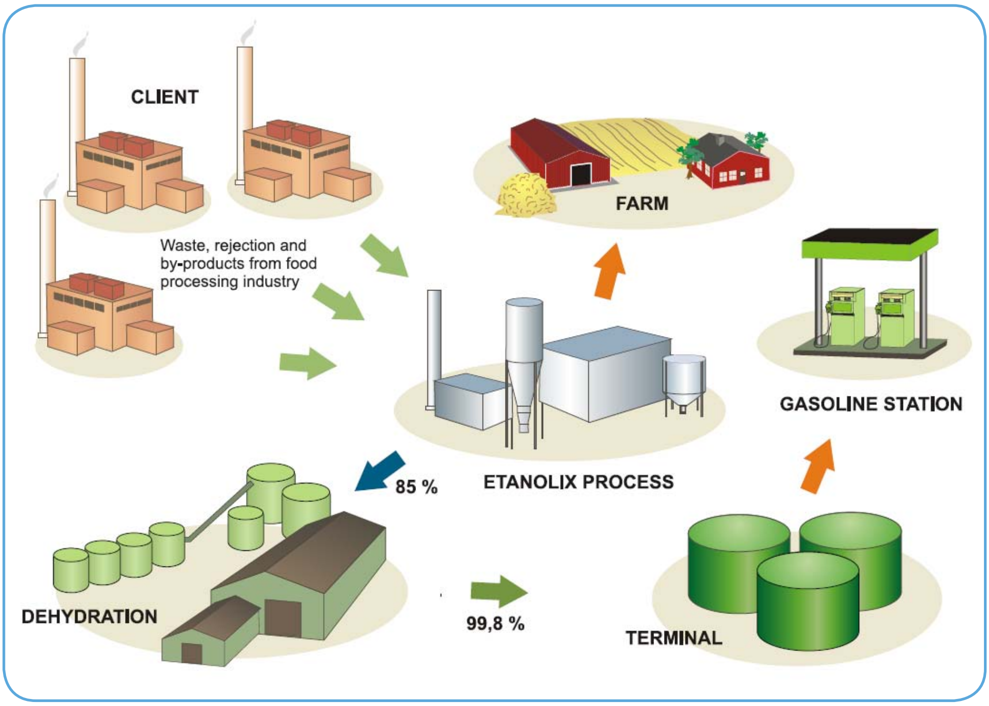

Figure 7. Etanolix concept of St1 (Growing Power, Tekes 2008).

12. Wind energy is growing most rapidly

The use of wind energy has grown rapidly throughout the world since the early 1990s. Current wind turbine technology has enabled wind energy to become a viable power source in today's energy market. The global capacity of wind power has exceeded 100 GW, representing roughly 1% of the total electricity generation. In the EU, wind energy counted for about 3% of all electricity produced. The global installed capacity of wind power is currently more than 20 GW per annum with increasing annual growth rates of about 20%. Wind power and its share in electricity generation is expected to double every 3 to 4 years in near future.

The growth in wind power will be distributed around the world, but the fastest rate of development is expected to be in Europe, North America, China and India.

Some countries have announced very ambitious goals: the aim of Denmark is to meet 50% of its electricity demand with wind by 2030.

13. Directions of further development

Modern wind turbines are ready for large-scale deployment and this deployment is already on its way. The aim of technological progress in wind turbines is to lower the production cost of electricity, to ease the construction and transportation of the turbines to difficult locations, and to better meet the requirements of the energy system.

The cost of produced electricity can be lowered either by increasing the electricity generation of the turbines or by decreasing the investment and maintenance costs of the wind power plant. The power system will benefit from turbines that can participate in the upkeep of the grid and from less variability in the power output of large-scale wind power production.

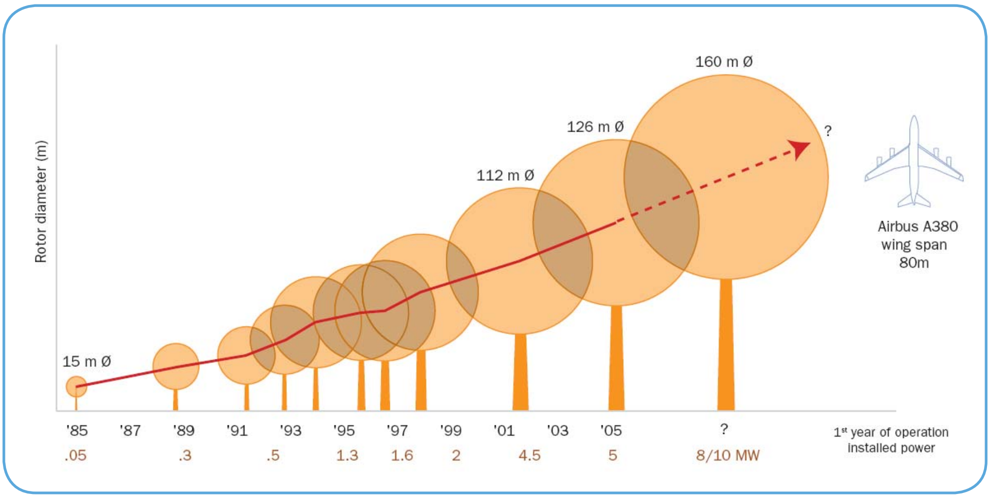

Figure 8. Increase in the capacity of wind turbines since 1985 (AWEA, WETP).

Land-based turbine size is not expected to grow as dramatically in the future as it has in the past. Larger sizes are physically possible (Fig. 8). However, the logistical constraints of transporting the components via highways and roads and of obtaining cranes large enough to lift the components present a major economic barrier that is difficult to overcome. Many turbine designers do not expect the rotors of land-based turbines to become much larger than about 100 m in diameter, with corresponding power outputs of about 3 MW to 5 MW.

A growing number of wind farms will be built on more complex terrains than the sites of most existing turbines. The logistical constraints limit the size of the turbine and pose requirements with respect to the loads, transportation, and reliable and efficient operation in gusty wind and icing conditions.

Offshore wind turbines do not face the same logistical hurdles. The largest current prototypes are in the range of 5–6 MW and larger turbines are in the design phase. Due to the more expensive foundations and grid connections per turbine, larger turbine size would be more optimal for offshore use. Large size becomes especially important for building offshore in deeper waters. However, the weight of the components will increase faster than the power output, although the use of lighter and more durable materials, real-time adjustments to varying conditions; and better design optimisation for site-specific conditions can be realised.

14. Integration of wind power into the energy system

At wind penetrations of up to 20% of gross demand (energy), system operating cost increases arising from wind variability and uncertainty has been estimated to about 1–4 €/MWh. This is 10% or less of the wholesale value of the wind energy. At higher penetration levels the costs are going to increase, but large cost increases are likely to occur only once there is excess electricity generation during several hours of the year or if the transmission system requires very large changes.

There are multiple ways to lower the costs of integrating wind power and enable higher penetration rates. The variation in wind power production decreases when wind power is aggregated from a larger area, as can be seen from the duration curves in the Fig. 9. Wind speeds between two locations far enough apart from each other do not correlate, and this yields smoothing of the aggregated output. Transmission lines are required to get the full benefits of this effect and this is one reason why there are plans to integrate the largely national power networks into continent-wide power grids, which could reach even further to bring renewable power from excellent resource locations to the consumption centres.

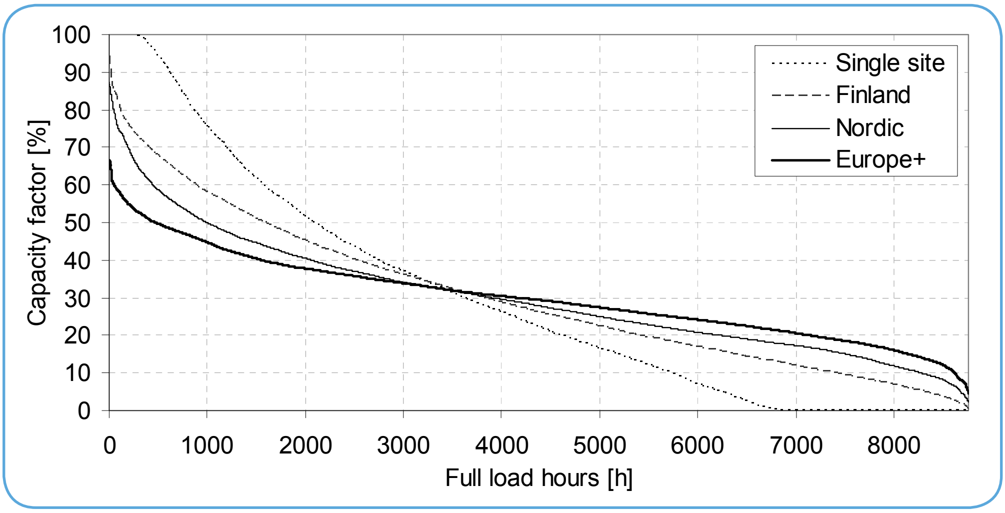

Figure 9. Approximate duration curves for wind power at different spatial scales. The time series has been scaled to have the same average capacity factor of 30%. Europe+ refers to Europe and parts of North Africa.

15. Solar energy could satisfy all energy needs

Solar energy forms in theory the largest available energy source. The incoming solar radiation on a global scale exceeds the global energy demand by a factor of 10,000. A surface area of just 130,000 km^2 in a dessert covered half with solar collectors (η=15%) could produce 10,000 Mtoe equivalent of energy – enough to satisfy all final energy needs. Or, an area of 20,000 km^2 located in the sunny Mediterranean would equal to the whole energy demand of the EU-27 (Fig. 10).

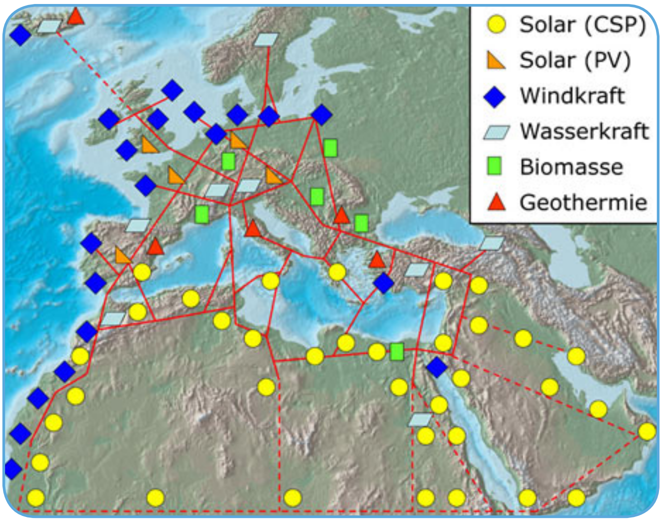

Fig. 10. A vision for large-scale solar utilisation with 400 GW of concentrating solar power, which would cover 10-25% of the total electricity demand in Europe (www.terc-eunema.org).

Thus, the solar radiation resource alone, though immense, does not provide an adequate base for a significant energy contribution. It needs to be attached to appropriate and efficient conversion technologies and to be complemented with other energy technologies or a balance of system components (BOS) to compensate for the intermittence, enabling full integration of solar into the energy systems. This challenge has not yet been met and solar energy utilisation in terms of energy relevance is still insignificant (about 0.1% of global primary energy). However, recent scientific discoveries, intensified technology development and possible breakthroughs in the coming decades may completely change the present marginality of solar energy and open up new avenues for solar energy as an important energy provider toward the middle of this century.

The main technologies available are solar heating for producing heat, solar photovoltaics for direct conversion of light into electricity, and concentrated solar power for electricity production through thermal solar power. Moreover, solar radiation could be employed for driving thermo- or photochemical reactions to produce useful chemicals or even fuel-like products, but these technology paths will most likely be less energy relevant in the future.

16. Possibilities of solar energy in Finland

The utilisation of solar energy in Finland is at present among the lowest in Europe. Installed PV capacity is around 5 MW_p (4–5 GWh per annum) and solar heating 15–20 MW_{th} (10 GW_{th} per annum). The industrial activities mainly for export markets are, however, relatively high or around 100 million €.

According to professor Peter Lund from Helsinki University of Technology, a share of 20% in the heating sector is technically quite feasible by 2050, and, if deployed in one million single-family houses, this would mean 4 TWh_{th} per annum. Summertime solar-assisted district heating systems may use some 2–3 TWh of solar heat as well. Equally, large-scale PV on roof-tops in urban and rural areas connected to the electric grid may become a reality by 2050. 1–2 kW_p of PV per dwelling could be a good design guideline to cause no major grid problems. This would add up to 2,000–4,000 MW_p of PV, or 2–4 TWh of solar electricity per annum. If, hypothetically, some 20% of all suitable surface areas in the built environment, such as south-orientated roofs or facades, were employed, the solar potential could rise to approx. 10 TWh per annum.

17. Summary of the possibilities to increase the use of renewable energy in Finland by 2020

VTT has made an estimate of the realistic possibilities to increase the use of renewable energy in Finland by 2020 using different levels of subsidies (Table 2). It can be noticed that the required demand (about 36 TWh) to cover the 38% share will be composed of several sources: hydro power, bioenergy, solar energy, wind energy and heat pumps. It is also obvious that present levels of subsidies and incentives are not adequate.

Table 2. Summary of the potential to increase the use of renewable energy in Finland by 2020.

	TWh
Incentives accelerate the increase	**Total 5 - 8**
- Large-scale hydro power	1 – 2
- Biogenic solid waste, low-cost biogas from landfills etc.	2
- More efficient use of biomass: drying of biomass, condensation of flue gases	1 – 3
- Wood for additional heating in buildings	1
Small subsidies needed, < 5 €/MWh	**Total 11 – 16**
- Heat pumps	2 – 5
- Solar heating	0,5
- Forest chips from final fellings	7
- Wood, pellets, bio-oils for primary heating buildings	(5-9)*
- Straw, reed canary crops if present subsidies for agriculture	1 – 3, up to 5
Subsidies needed 5-20 €/MWh	**Total 8 - 16**
- Forest chips from young stands	4 – 12
- Electricity from small-scale CHP plants	(1-2 power)*
- Wind power: coasts and mountains	4
High subsidies, > 20 €/MWh	**Total 8 - 12**
- Synthetic diesel oil from imported biomass	0 – 4
- Wind power: off-shore and inland	6
- Biogas, other sources than landfills	2
TOTAL	**32 - 52**

* Do not increase the total use of renewable energy because it is included in other figures.

The most important uncertainties concerning the presented estimate are connected to the production level and structure of the forest industry, because its role is dominating the resources and use of bioenergy in Finland. Another significant uncertainty is the role of biomass trade in the future: differences in national subsidies can lead to large-scale exports and imports of biomass-based fuels within the EU and also on other continents.

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Title

Towards zero emission energy production

Abstract

If the global temperature rise is to be limited to 2°C compared with the pre-industrial temperature level, global greenhouse gas emissions will have to be reduced by 50–85% from the current levels by 2050, according to the IPCC. Furthermore, the industrial countries will have to cut their emissions by 80–95% by 2050 and by 25–40% by 2020 to achieve this warming limit.

The EU has unilaterally undertaken the commitment to reduce emissions by 20% by 2020, and has also proposed indicatively to cut its emissions by 60–80% by 2050. Finland is a part of European Union and the policies of the EU play a very crucial role also in the Finnish energy economy.

In Finland, greenhouse gas emissions can be reduced by 60–66% from 1990 to 2050 according to the scenario study presented in this publication, if the emission rights price rises no higher than 80 €/tCO2-eq. Increased energy efficiency becomes an important factor in emission reductions.

The most important energy production technologies which reduce emissions are bioenergy technologies, nuclear power and wind power. The latest technological developments, as well as the possibilities and the role of different energy production technologies in climate change mitigation are described in this publication.

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The future climate policy will be one of the most prominent drivers of energy technology markets. If the global temperature rise is to be limited to 2°C compared with the pre-industrial temperature level, global greenhouse gas emissions will have to be reduced by 50–85% from the current levels by 2050, according to the IPCC. Furthermore, the industrial countries will have to cut their emissions by 80-95% by 2050 and by 25-40% by 2020 to achieve this warming limit.

Climate change mitigation will require transition towards low emission energy systems. This will incur expenses but it will also create huge markets for low emission energy production, renewable energy solutions and energy saving technologies. In Finland, the demand that renewable energy should be responsible for 38% of the final energy consumption can only be met by using several means like hydropower, bioenergy, wind energy and heat pumps. One option for achieving the target of low emissions is to maintain or strengthen the role of nuclear power.

The availability of and demand for energy probably mean that fossil fuels will continue to play a key role in the energy mixture of the future. Naturally, the challenge is to reduce dramatically the greenhouse gas emissions of power generation based on fossil fuels, but there are several options available and carbon capture and storage (CCS) technologies are under development and demonstration.

Global energy questions need global political decisions. Technology can provide solutions but implementing and regulating the use of energy demands political will and commitment. In the climate mitigation process, this political will is on trial. The EU has unilaterally undertaken the commitment to reduce emissions by 20% by 2020, and has also proposed indicatively to cut its emissions by 60-80% by 2050. Finland is a part of European Union and the policies of the EU play a very crucial role also in the Finnish energy economy.

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