

energy visions



2050

Summary

ENERGY VISIONS 2050 - SUMMARY

VTT Technical Research Centre of Finland published a book entitled 'Energy Visions 2050' in June 2009. The book deals with the long-term (by 2050) development of the energy sector from a global perspective. It includes assessments of technology development and future technologies throughout the energy system, i.e. energy resources, energy conversion, transmission, distribution and end-use.

The book presents energy scenarios obtained from model calculations. The results provide indications of the structure of future energy systems, assuming the greenhouse gas emission reductions needed to tackle climate change are optimally implemented.

energy visions 2050

In June 2009, VTT Technical Research Centre of Finland published a book entitled Energy Visions 2050, which reveals the central future challenges facing the global energy system and the future development of clean energy technologies. The book examined ways of addressing the challenges involved in tackling climate change without hampering human wellbeing, applying global modelling as tools for analysing different development paths for the global economy and energy systems. The timeframe spans up until the year 2050.

The contents of the book covers the whole energy chain: future technologies for energy conversion, end-use, transmission and distribution. Furthermore, a comprehensive outlook for energy resources is included in the book. This summary presents highlights and key messages of the results of the book.

The book includes separate sections entitled 'vision boxes', which deal with various topics. In most cases these boxes discuss more visionary ideas, the realisation or wide penetration to the markets not necessarily even seem probable within the timeframe of the book. A couple of examples of vision boxes are also presented in this summary.

The results presented in the book, obtained through broadly based and national and international co-operation, introduce a Finnish vision of the potential for technology development in meeting the global energy challenges of the future, especially climate change.

The Energy Visions 2050 project was funded by the ClimBus Programme of Tekes (Finnish Funding Agency for Technology and Innovation), VTT and the Government Institute of Economic Research (VATT).

GLOBAL CHALLENGES AND THEIR IMPLICATIONS FOR THE ENERGY SECTOR

The main global drivers of the energy system are the **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.**

Globally, the annual growth in primary energy use has been on average almost 3% in the beginning of the 21st century. Much of the growth can be traced back to rapidly developing economies, especially China and India. The global demand in terms of primary energy was about 490 EJ in 2006. Today, over 80% of the global energy supply is based on fossil energy sources, the most important being oil (35% of global primary energy supply), coal (26%) and natural gas

(20%) (IEA 2008).

Energy production, as it is today, causes acidification and air quality problems and, especially, greenhouse gas emissions that are seen as the main contributor to climate change. The most important greenhouse gas from energy production is carbon dioxide (CO₂). Climate change is widely acknowledged as the largest environmental risk globally.

The energy sector is presently the largest source of greenhouse gas emissions on a global scale. The stabilisation of the atmospheric greenhouse gas concentrations at a safe level requires very deep emission reductions in the long term. In addition, the global CO₂ emissions should peak between 2000-2015, i.e. start declining within the next few years at the latest. The history of CO₂ emissions from the energy sector and the scale of the mitigation challenge in the coming decades is illustrated in Figure 1.

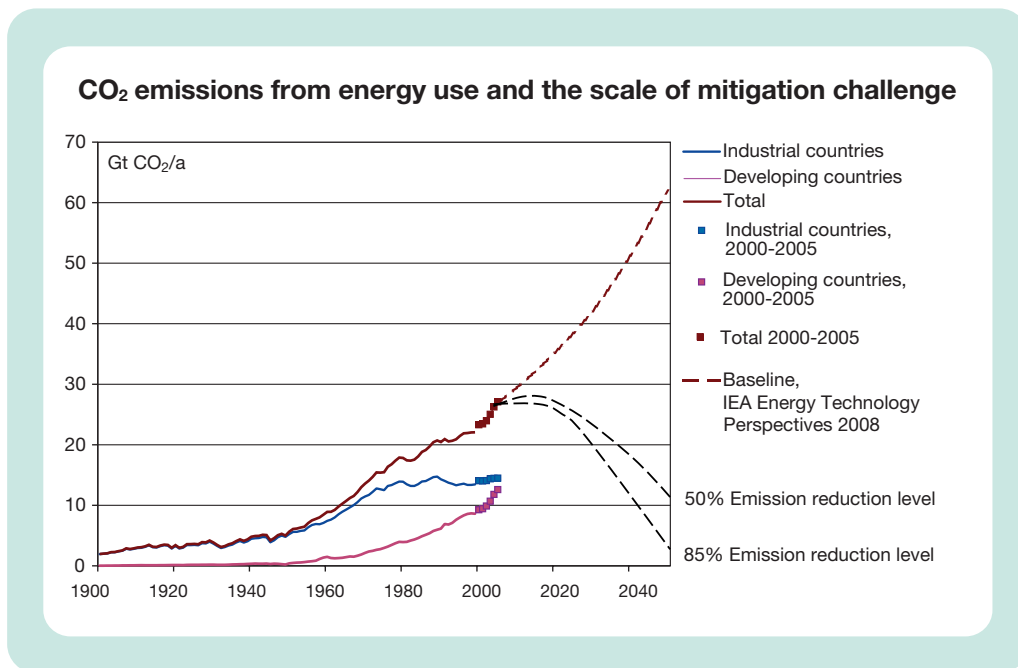


FIGURE 1. CO₂ emissions from fossil energy use for the industrial countries (s.c. Annex I countries) and the developing countries (other than Annex I countries). Emission history for 1900-2005 and emission reduction scenarios for limiting the emissions by 50% and by 85%, corresponding to the upper limit emissions and lower limit emissions for a temperature rise level of 2 °C according to IPCC (2007). (Data sources: CDIAC, IEA, VTT, CAIT)

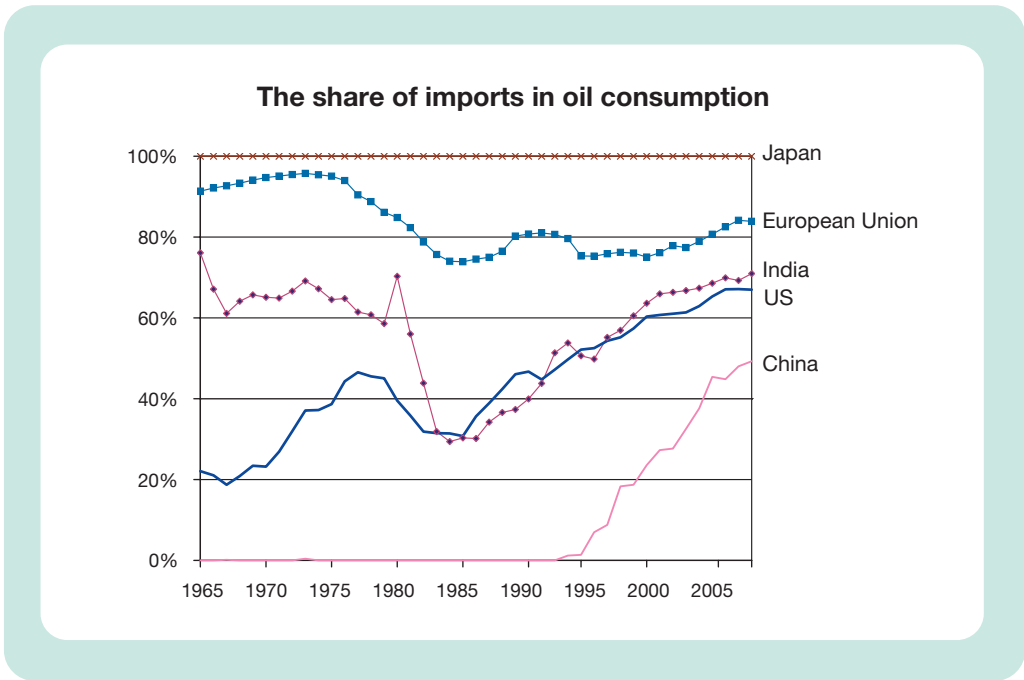


FIGURE 2. The imported share of oil consumption in some countries and in the EU. The share of imported oil in the EU and USA decreased after the oil crises in the 1970s and 1980s, but in recent years oil imports have increased. Oil imports to China and India are also increasing. (Data source: BP 2008)

The conventional energy resources of the world, especially in case of oil and gas, are very concentrated. According to many studies, oil and gas production based on conventional resources are expected to peak in the coming decades. Many countries are highly dependent on imported energy (see e.g. Figure 2 on imports of oil). Often this is thought to expose the country to crises concerning the price and availability of energy. The development trend has implied increasing discussion on the need for improvement of energy security of countries or groups of countries. This is considered to be one of the central drivers affecting energy sector development in the future.

The developed countries and the developing countries are still in very different situations with respect to energy-related challenges. In the developing countries there are one and a half billion people without access to modern energy services, which is a serious obstacle to development. In the devel-

oped countries the problems arise from the ageing energy systems and large greenhouse gas emissions. Environmentally sound energy solutions are also required in the developing countries, where the energy need is rising rapidly.

Revolutionary changes are needed in the energy sector in order to cope with the future challenges. Principal measures related to meeting the challenges of mitigation and climate change, security of energy supply, as well as economic and environmental challenges, can be divided into two categories: 1) measures enabled by technology and 2) measures enabled by changes in the structure of consumption. These categories are, however, not independent of each other. The main emphasis in Energy Visions 2050 is on measures enabled by technology, but changes in the structure of consumption are also dealt with to some extent.

More efficient technologies with regards to energy conversion and end-use should be

intensively developed, and carbon-neutral and low-carbon energy sources (renewable energy sources and nuclear energy) as well as carbon capture and storage (CCS) technologies need to be favoured. Adoption of novel energy technologies form carbon-neutral and low-carbon sources involves challenges and development needs for energy supply systems, e.g. electricity infrastructure including power transmission and distribution.

Technological development has considerable inertia; it is typically a slow process. The development of a technology from the laboratory to widespread market penetration can take decades. There are two types of inertial aspects in the case of energy technology. These are, first, the innovation process and, second, the slow penetration to the real energy system.

Energy technology is often very capital intensive and it is characterised by long life-times of investments. This slows down

the changes in the energy sector. The typical life-times of infrastructure investments and buildings are of the order of fifty to a hundred years. The life-time of hydro and nuclear plants can exceed 50 years, and in the case of fossil-fuel-fired plants the life-time may also be several decades. Industrial plants in energy-intensive industries typically have life-times of two decades or more. Cars are used typically from ten to fifteen years and domestic electrical appliances also for several years. Due to the inertia, long-term analysis up to 2050 can be regarded as feasible in the context of the energy sector.

ENERGY USE

Energy is used widely in society, but ultimately by consumers. Visions, technology opportunities and their potential presented in Energy Visions 2050 are reviewed in the following by end-use sectors, i.e. industry, buildings (residential and commercial) and transport.

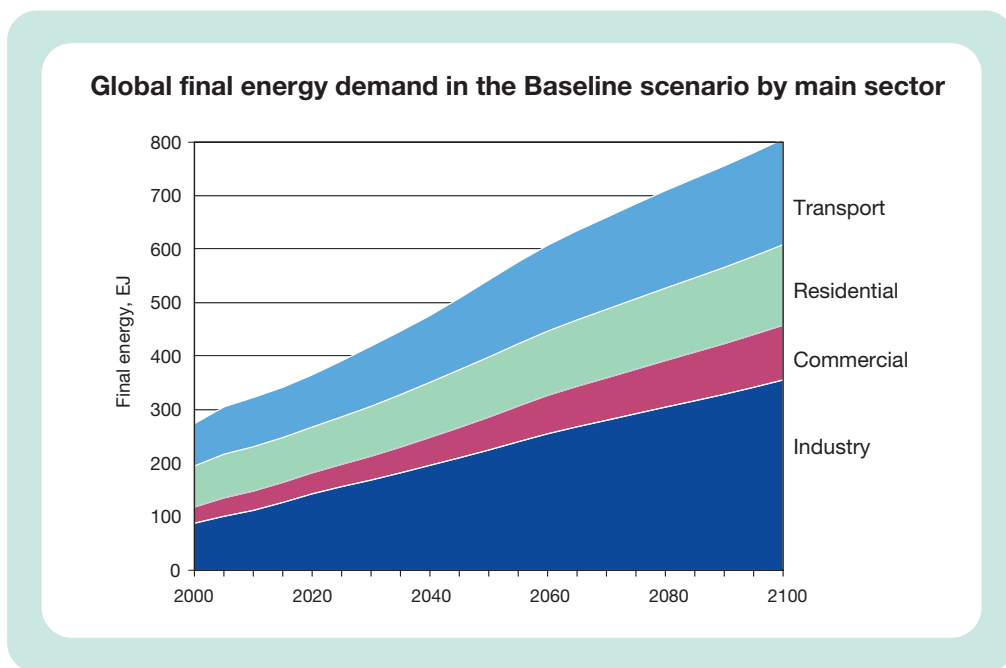


FIGURE 3. Global final energy demand of the Baseline scenario in Energy Visions 2050 by main sector. Industrial and commercial final energy usage increases most rapidly.

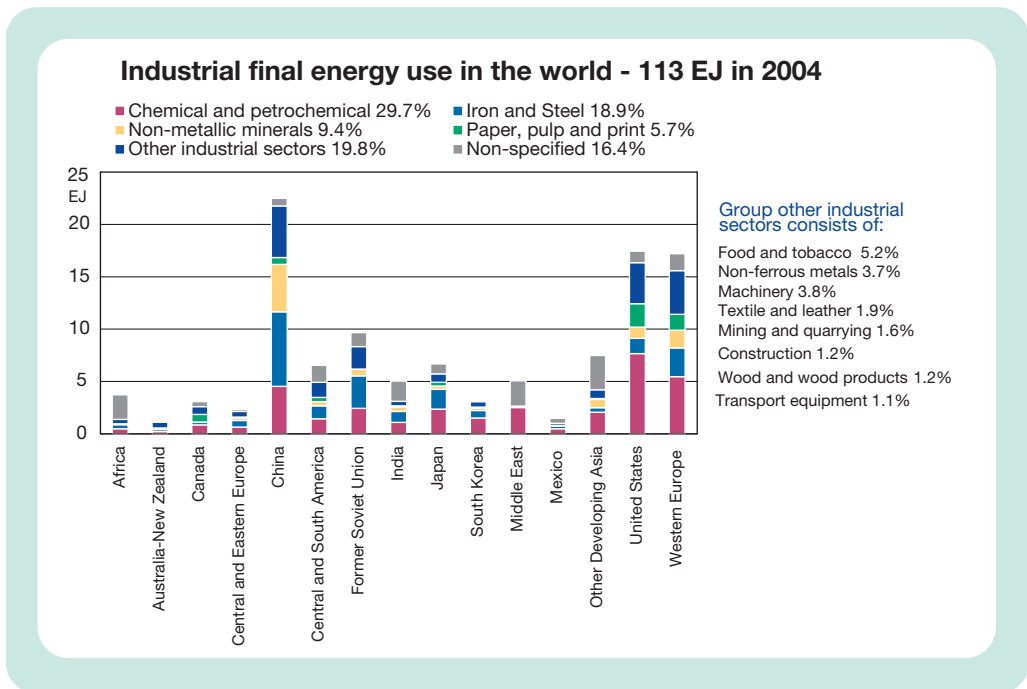


FIGURE 4. Energy consumption by industrial sector. Energy consumption in regions is dependent on e.g. the industrial structure, population and development phase. For example, overall consumption in Japan is higher than in India despite a tenfold difference in population. The chemical, petrochemical and iron and steel industries account for roughly half of the total global final energy use in industry. (Data source: IEA)

The concept of energy efficiency and its improvement have particular significance when future energy use is analysed. Simply put, this means introducing technology or adopting new operating practices that require less energy input to produce the same product or service, thereby improving energy security and reducing environmental effects of energy production.

Industry

During the development of industry, energy consumption has increased in relation to production volumes. In the past, industrial energy use and GDP were strongly connected, but recently the growth of the ICT and service sectors has reduced this dependency. The trend in many products has been towards higher added value, which has

often meant higher energy input. This development has been compensated by process development, which has raised energy efficiency. Energy efficiency should be an integral part of process and product design and operation. The most important choices are made during the design and construction phase.

Globally, the most important industrial sector with respect to energy use is the chemical and petrochemical industry, with some 30% of global final industrial energy use in 2004, followed by iron and steel (19%) and non-metallic mineral industries (9%). Paper, pulp and print is the fourth largest specified category (6%); however, in the Finnish context, this category has traditionally been the most significant industrial sector. Altogether, these four industrial sectors accounted for over 60% of

TABLE 1. Long-term potentials for energy-efficiency improvement of some industrial products. There are significant differences between products with regard to the present state and theoretically achievable levels. The abbreviation SEC stands for specific energy consumption. (Turkenburg 2007)

Long-term potentials for energy efficiency improvement			
SEC's in GJ/ton product	Present best	Prospective technology	Theoretical minimum SEC
Paper/board	2.3-8.6	0.6-4.3	0.0
Primary steel	19.0	12.5	6.6
Secund. steel	7.0	3.5	0.0
Ammonia	33.0	28.6	19.2
Nitric acid	26.8	15.3	3.2

industrial final energy use in the world in 2004 (Figure 4).

Energy consumption in industry can be divided into consumption of the process and consumption of the auxiliary functions (space heating, lighting etc.) In all processes thermodynamics sets the theoretical minimum for energy consumption. For example, water evaporation needs a certain amount of energy, as do chemical reactions. These limitations might be overcome by redesigning the process concept, e.g. papermaking without water as a process medium. Another option is to replace the current energy input with a lower grade of energy, like low-temperature waste heat streams. Major improvements thus require fundamental changes in the process, but there is still plenty of potential to improve current systems. Even if the main process is found to be near its minimum energy consumption, the auxiliary operations may offer possibilities for substantial savings.

Industrial processes are quite different in their energy requirements and energy efficiency, and even similar processes have a lot of internal and external factors that make them unique in this sense. Thus, tech-

nological opportunities within different industrial sectors are numerous. Table 1 illustrates long-term potentials for the energy efficiency improvement of some industrial products. One can see that there are significant differences between present best and prospective technologies and theoretical minima, i.e. the potential to improve energy efficiency in the manufacturing of industrial products. The sections describing technology developments for different industrial sectors in Energy Visions 2050 include a more detailed analysis of future technology opportunities for industry, complemented with a section on generic technologies common to all the sectors.

Building sector

In the building sector (i.e. residential and commercial sectors), the main end-uses of energy include space heating, hot water production, cooling, lighting, cooking, and various electrical appliances. When improving the energy efficiency of buildings, and decreasing CO₂ emissions, there are two major steps: (i) reduction of building-level overall energy demand, and (ii) fulfilling reduced energy demand by utilising primarily renewable energy sources.

In order to reduce overall energy demand in the building sector, a holistic approach and professional planning are strongly recommended. Such an approach allows comprehensive planning and design of building architecture, structural components, electricity, building automation, and all building service system solutions.

Typical technical life-cycles in our built environment are several decades, and major changes in the building stock take place quite slowly. Therefore, it is very important to make wise and sustainable decisions when balancing energy demand and supply – on both regional and individual building levels. Technology development of building

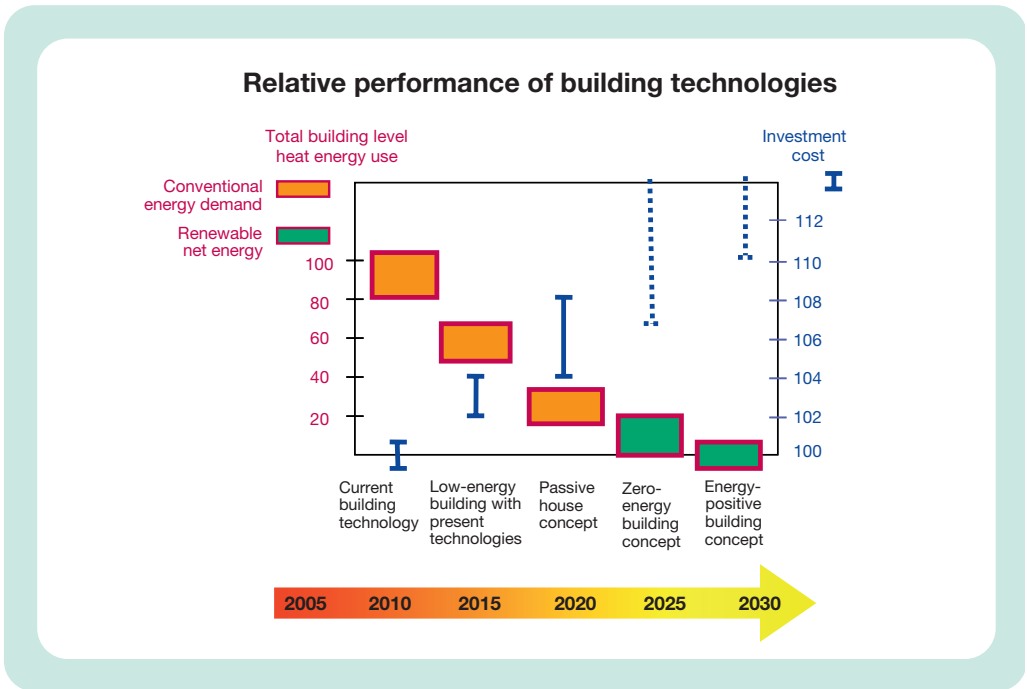


FIGURE 5. Relative heating energy demand and investment cost of energy-efficient buildings compared with current building technology according to a Finnish full-scale demonstration project. Additional investment is very low compared with e.g. market price fluctuations or choices in the standard of interior equipment.

and construction components over the past two decades, together with careful planning and design methods for the future built environment, has opened a huge energy-saving potential throughout the building sector. According to several demonstration projects, this saving potential can be more than 50% with marginal additional life-cycle costs (see Figure 5).

The market situation for the energy-efficient building concept seems to be in the early development phase, but it is expected to strengthen in the near future due to environmental, economic and political reasons. Realisation of the global building sector's CO₂ emission mitigation potential requires dramatic changes in building-related regulations and conventions.

According to dozens of international demonstration cases, an energy-efficient building is also a good investment. Though the initial construction costs of a low-ener-

gy building with present technologies are 2-5% higher than for a conventional building, these costs are recouped in energy savings over 5-15 years.

Figure 6 shows the relative shares of space heating and other uses (including hot water production, cooling, lighting, cooking, and various electrical appliances) in global final energy consumption according to the scenarios presented in Energy Visions 2050. The share of space heating was about one-third of the total final energy in 2005, but according to the scenarios it will be considerably reduced by 2050.

In many countries, the efficiency of space heating is still rather poor and, therefore, large improvements can be achieved. On the other hand, the use of energy for cooling and for various electrical appliances is projected to increase rapidly in developing countries. Reducing stand-by power consumption of domestic appliances and

introducing LED technology in lighting of-fer significant electricity saving potential in the residential sector.

Transport sector

Changes and trends in the society and economy that create the need to move goods and people are inevitably mirrored in transport and traffic. A proof of this is that for decades the growth of GDP was matched with equal or even greater growth in transport volumes. Only in recent times has this trend shifted in response to the increasing focus of value-creation on immaterial products and services. The average fuel consumption of new cars has decreased significantly in recent decades as the efficiency of engines has improved. However, the consumer trends have been towards larger and more powerful cars. Many competitors and alternatives to the internal combustion engine (ICE), such as electric cars and hybrids, are

being developed and evaluated, but it is still too early to judge which ones, if any, will survive and become the new mainstream technology.

Nevertheless, it is more than likely that diversification in terms of transport-related energy sources and prime movers is going to increase drastically from the present-day situation of oil and ICE dominance. The greatest change in the near future will be in the use of biofuels together with oil-based fuels.

According to the Baseline scenario of Energy Visions 2050, energy for transportation would increase by over 60%, and CO₂ emissions by about 40% by the year 2050, as compared to 2005. Aviation is the fastest growing mode, but road transportation is also growing very rapidly in developing countries. For example, in developing Asia, the volume of passenger car travel is projected to be as much as six times as large in 2050 as in 2005.

The potential for technology development

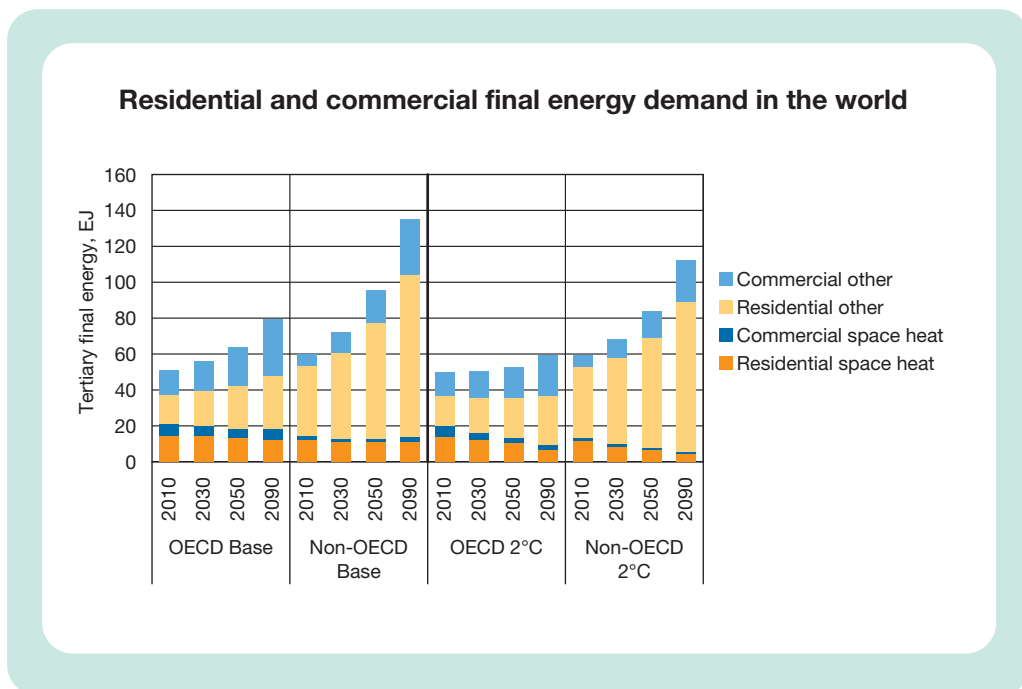


FIGURE 6. Residential and commercial final energy demand in the scenarios of Energy Visions 2050. The share of energy used for space heating would be considerably reduced.

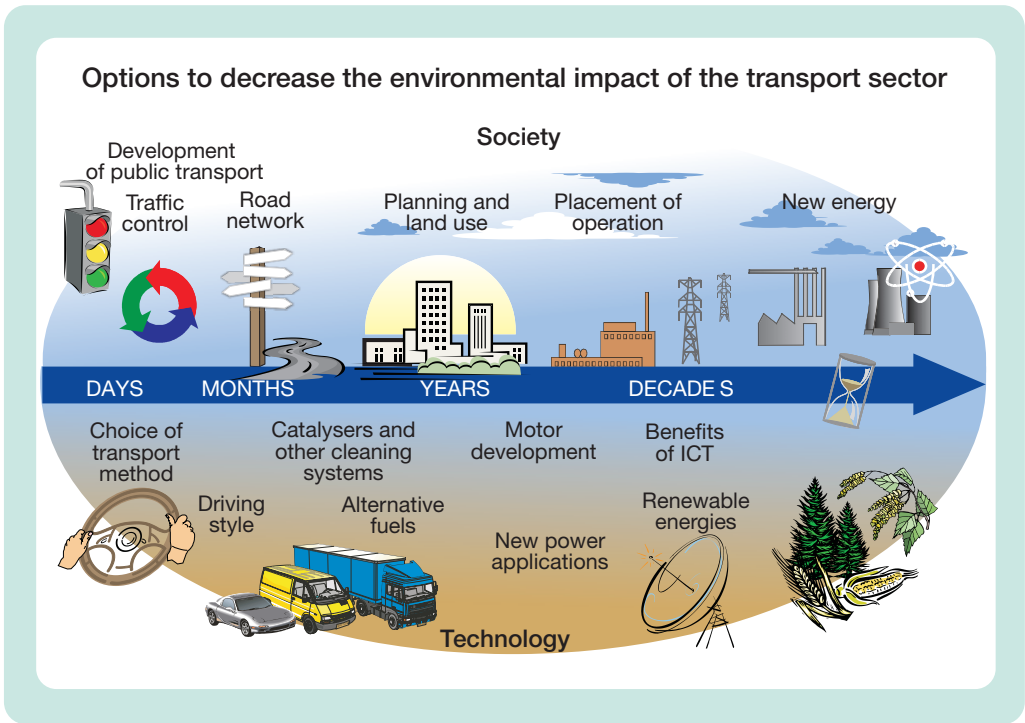


FIGURE 7. Options and their time span to decrease the environmental impacts of the transport sector. Depending on the option, there is a significant difference in time needed for implementation.

in the transportation sector is substantial, but the technological transition required for deep emission cuts also presents enormous challenges. During recent years, fuel efficiency in all transport modes has been improving quite favourably, and this trend is assumed to continue in the scenarios.

Additional efficiency improvements and emission reductions are achieved in scenarios where the aim is mitigation of climate change (the '2°C' scenarios in Figure 8). In these scenarios, alternative fuel vehicles start penetrating into the market. The use of biofuel components in diesel engine vehicles is already feasible at present, and the proportion of the biofuel component can be technically increased to a very high level by 2050. Hybrid electric vehicles and plug-in hybrid electric vehicles have already entered the market and represent feasible near-term options for the transition to full electric vehicles. Another important long-

term technology alternative is fuel cells, in particular hydrogen-fuelled cells. In the 2°C scenarios, electric vehicles turned out to be a more competitive alternative in the light-duty vehicle categories. Hydrogen fuel cell vehicles gained notable market share primarily in heavy-duty transportation after 2050. Nonetheless, large uncertainties are embodied in the results for the transportation sector due to immature technologies and especially due to the uncertainties related to future policies and regulations made nationally.

ENERGY CONVERSION TECHNOLOGIES

The energy conversion technologies reviewed in the Energy Visions 2050 represent possibilities to reduce greenhouse gas emissions from energy production and to

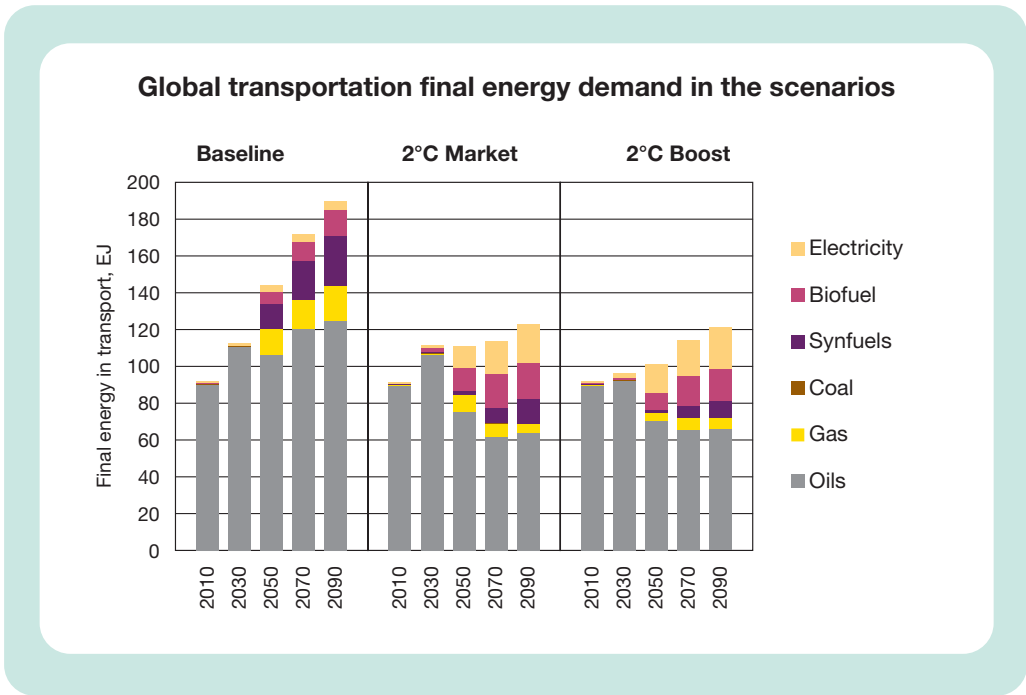


FIGURE 8. Transportation final energy demand in the scenarios of Energy Visions 2050. Electric vehicles penetrate the market for low-duty vehicles under the 2°C target.

reduce the use of depleting fossil resources by means of renewable energy, near-zero-emission technologies and conversion processes of greater efficiency.

Most of the conversion technologies introduced and assessed aim at electricity production or the production of liquid and gaseous biofuels to replace fossil oil and natural gas. The focus of liquid and gaseous biofuels is on the transport sector, but applications in residential heating and industrial processes are also included. Large-scale heating, such as in municipalities and industry, is covered by novel combined heat and power (CHP) conversion technologies. Small-scale heating technologies are limited to solar heating, CHP based on fuel cells, and novel slow-heat-release appliances with high efficiencies and low fine particle emissions.

Technological possibilities to improve the competitiveness of renewable electricity generation by converting energy from

wind, biomass, the sun, the oceans, and waterfalls are dealt with in *Energy Visions 2050*. The future development steps for nuclear power and carbon capture and storage (CCS) from fossil fuel plants are presented as near-zero-emission technologies.

The prospects for nuclear power are characterised by the future plant options, which include several advanced concepts such as fast reactors with closed fuel cycle enabling much more effective use of uranium resources and thus providing a long-lasting basis for electricity production. Furthermore, some of the new concepts could also serve as co-producers of process heat or hydrogen. The spent fuel repository, for which the construction licence application is planned to be submitted to the authorities by 2012, is an example of Finland's efforts in this international sector. Energy from the fusion of heavy hydrogen fuel (deuterium, tritium) is actively being pursued as a long-

Vision box: 5 million electric vehicles in the Nordic countries – impacts on the electricity system

What will happen to the electricity system if half of all personal vehicles in the Nordic countries are turned over to electric vehicles (EV) or plug-in electric vehicles (PHEV)? The yearly increase in consumption is less than 4%, or approximately 14 TWh. And the effect on the system peak load, assuming;

- all cars are charged through household outlets (max 2500 W), and
- the charging system is smart enough to move 90% of all evening activities to after midnight,

can be seen in Figure 9. The peak load week from 2006 is used as the basis. The peak load increases by less than 2%, and electricity consumption is not that noticeable.

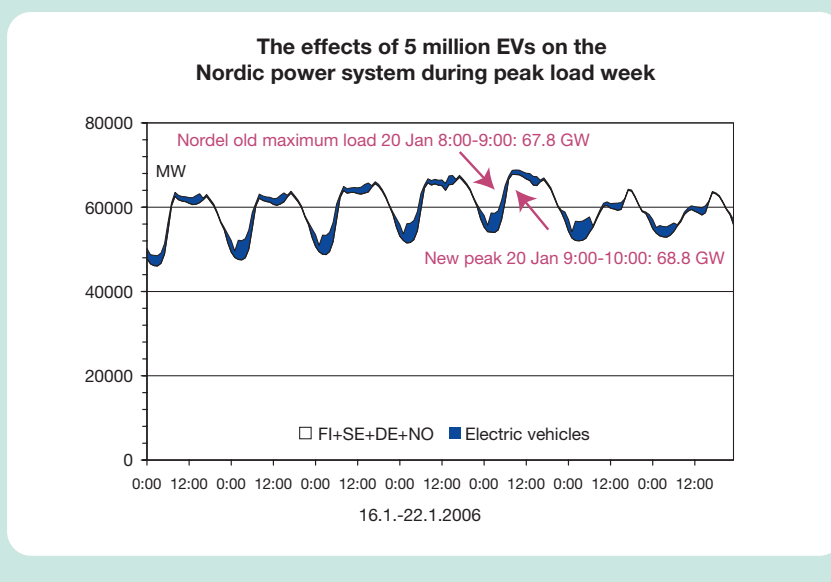


FIGURE 9. The effects 5 million electric personal vehicles on the Nordic system during peak load week. Year 2006 actual peak load week was used.

term, almost inexhaustible supply of energy. The scientific feasibility of fusion energy has been proven, but technical feasibility remains to be demonstrated in experimental facilities. Upon successful demonstration of fusion power production, commercialisation of fusion is contemplated to begin at the earliest in about 2050.

The possibilities of CCS in connection with oxygen combustion in fluidised bed boilers, which provides an option for new large CHP and mid-scale (600-800 MWe)

coal and co-firing plants, as well as retrofits of existing plants, are the main focus of the present development activities in Finland. Also, integrated plant concepts based on fluidised bed pressurised gasification are especially feasible for CCS.

Centralised, large-scale bioenergy utilisation is dependent on an efficient procurement system to enable the harvesting or collection, transportation and storage of huge volumes of biomass from fields or forests to the plant. The most efficient and

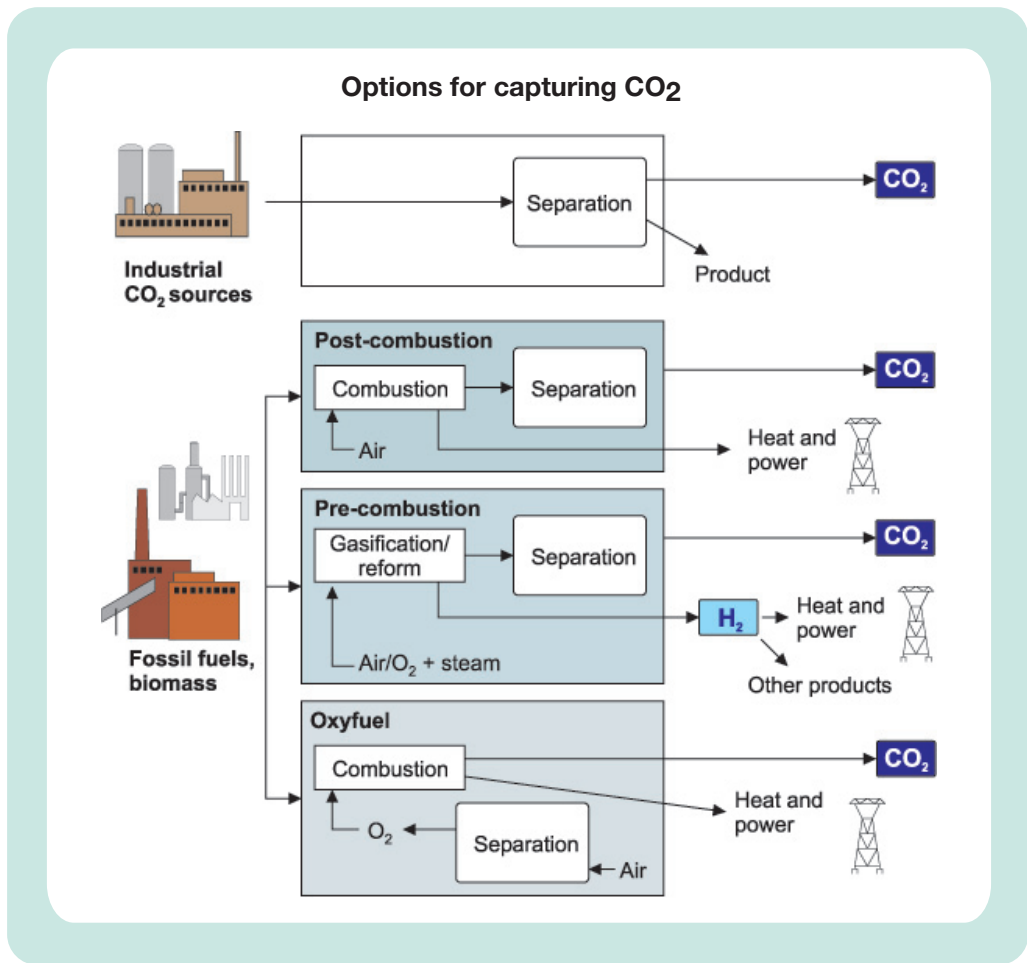


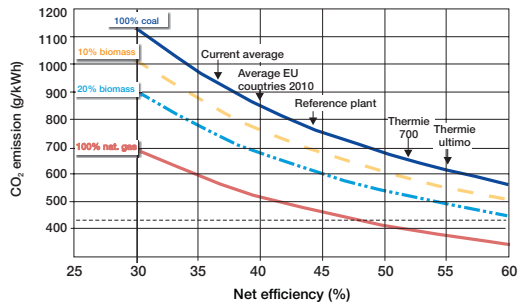
FIGURE 10. Options for capturing CO₂. There are three main methods for capturing generated CO₂, the choice of which is dependent on the power plant type to which CO₂ capture is applied: post-combustion, pre-combustion, and oxy-fuel combustion systems. The separated CO₂ is compressed and transported by pipeline or tankers to the storage site. Suitable storage sites include exhausted oil and gas fields and other subterranean geological formations, such as saline aquifers. Applying CCS technology to power plants would reduce the CO₂ emissions from combustion by 80-90%. The removal of CO₂ is applied, to some extent, in industrial processes. (Based on IPCC 2005)

economic concepts of bioenergy utilisation are typically integrated into processes where biomass is primarily utilised as a raw material and its residues or waste are used for energy production. A classic example is the pulp mill, where fibres of wood are utilised for pulp production, and the rest of wood for energy production in excess of the mill's own consumption. Integrated energy production at the mill can presently include steam and electricity from CHP

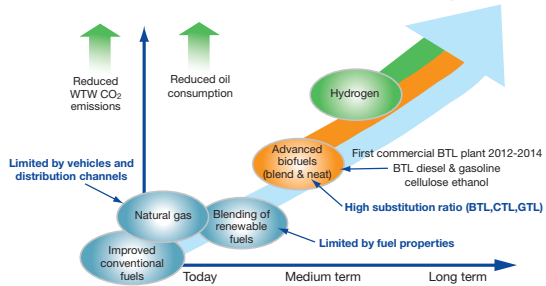
plants, as well as tall oil and pellets from by-products and residues. In the future, the production of liquid biofuels for transportation will often be integrated industrial processes in the forest, food, waste recycling and other industries where biomass is used as a raw material of the industrial processes. Biomass is also a feasible option for co-firing and co-gasification with fossil fuels in CHP plants in industry and municipalities.

DEVELOPMENT OF ENERGY CONVERSION TECHNOLOGIES

CO₂ emission reduction possibilities with supercritical boilers

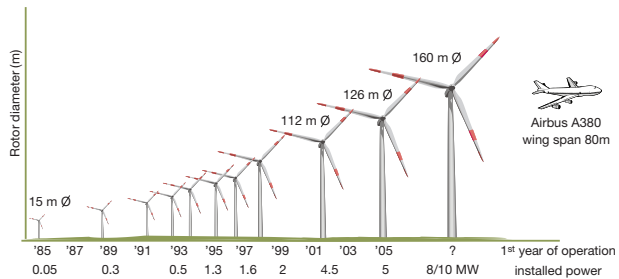


Roadmap for future transportation fuel technologies

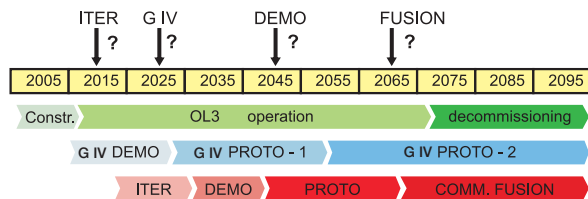


Modified from Røj 2005

Development of wind turbine technology from 1980's to 2010

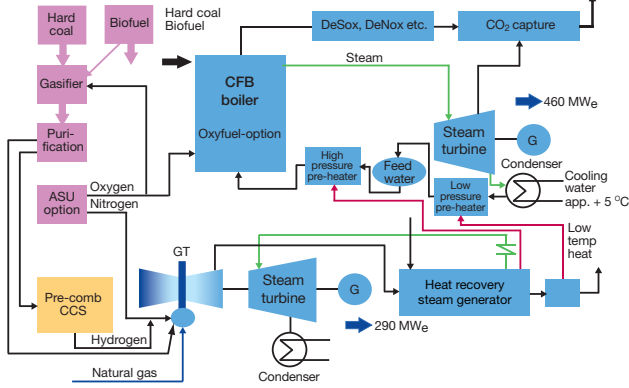


An indicative timeline for the emergence of new types of nuclear reactors



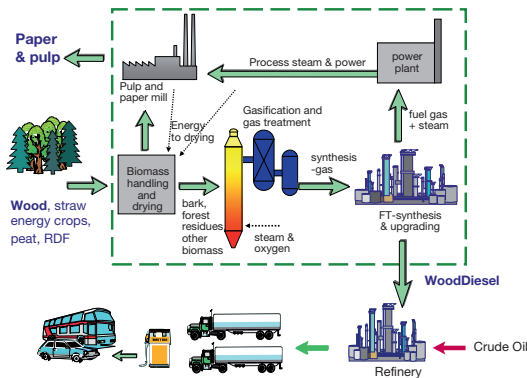
NOVEL ENERGY TECHNOLOGIES FROM FINLAND

Step-wise built multifuel high-efficiency CHP with carbon capture

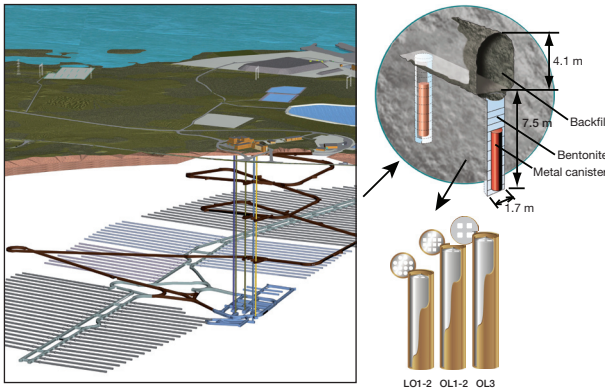


Pohjolan Voima

Integration of FT synthesis plant to a pulp and paper mill



Repository for spent nuclear fuel



Vision box: Bioenergy CCS

In principle, carbon capture technologies could be applied to separating the CO₂ originating from biomass, provided the power plant is of sufficient size to justify the cost. Considering the whole life-cycle of biomass, the application of CCS to biomass energy conversion would generate negative atmospheric carbon emissions.

Biomass bears certain similarities to the fossil fuels, particularly coal, that apply to energy conversion technologies and the range of energy products that can be generated, i.e. dispatchable, base-load electricity, as well as liquid and gaseous fuels. Therefore, all three technological routes for CCS could be applied to biomass energy systems. However, due to the large additional consumption of energy related to current capture technologies, its application could only be considered in respect of large-scale (> 500 MW) power and heat plants. Since the majority of biomass-fired boilers available are typically smaller than what are considered viable, practical CCS potential would be limited to black liquor recovery boilers and a few CHP plants.

The ambitious goal of the EU's Biofuel Directive to significantly increase the use of biofuels could provide additional CCS opportunities. Several biofuel refining processes produce CO₂ gas as a by-product, which could, with relative ease, be dehydrated, compressed and transported for storage. The EU goal of 10% by 2020 would increase the annual use of biofuels to over 40 Mtoe in the EU. If half of these production facilities were suitable for the application of CCS, and the share of ethanol and synthetic diesel were, for example, 10 Mtoe ethanol and 10 Mtoe synthetic diesel, then the annual CCS potential would be about 10 Mt CO₂.

Biomass could also be co-fired in CCS-equipped coal-fired boilers, which would further reduce the CO₂ emissions from the power plant. The use of biomass is governed by local availability and the cost of biomass. It is likely that biomass co-firing would be used predominantly as a means of reducing CO₂ emissions in boilers not equipped with CCS. One can see the potential for bio-CCS in the climate change mitigation scenarios of Energy Visions 2050. In the long-term future, bio-CCS appears to be a notable option, significantly penetrating into the energy systems beyond 2050 (see Figure 11).

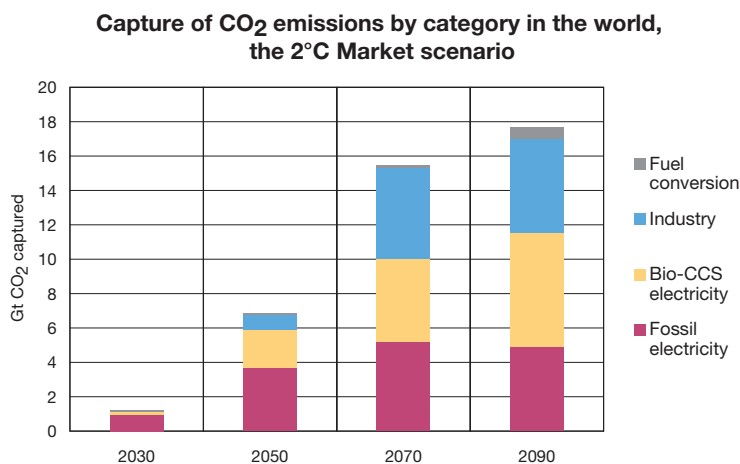


FIGURE 11. Capture of carbon emissions by category, '2°C Market scenario' aiming to mitigate climate change. Biomass-fuelled plants equipped with CCS appear to represent a significant and cost-effective mitigation option.

ENERGY RESOURCES

The use of fossil fuel resources (oil, natural gas, coal) has made it possible to establish the industrial community, and has provided the means for the developed countries to become increasingly more prosperous. A supply of secure, equitable and sustainable energy is vital to the future prosperity of the developing countries, too. The historical development presently faces at least two types of challenges. The resources of fossil fuels are limited and are rapidly being depleted. The present easily exploitable reserves of crude oil and natural gas are estimated to be exhausted within 40 to 70 years. However, there are probable additional resources that can be recovered at higher costs and with larger energy inputs required for their refinement. The easily accessible reserves of

coal are about twice as large, and probable additional resources would last for centuries at the current energy consumption level.

The world energy supply is predominantly based on fossil fuel reserves and will be for several decades to come. The ultimate origin of fossil fuel resources is solar energy, which provided the energy needed for the historical accumulation of large amounts of biomass, followed by transformations through geological processes. In fact, the most important present renewable energy sources are either indirectly (bioenergy, wind and hydro) or directly related to the availability of abundant solar energy.

The surface of the Earth receives solar insolation at an average rate of 81,000 TW a year. This can be compared with the current average energy consumption flow of about 16 TW (490 EJ/year). It is evident that solar

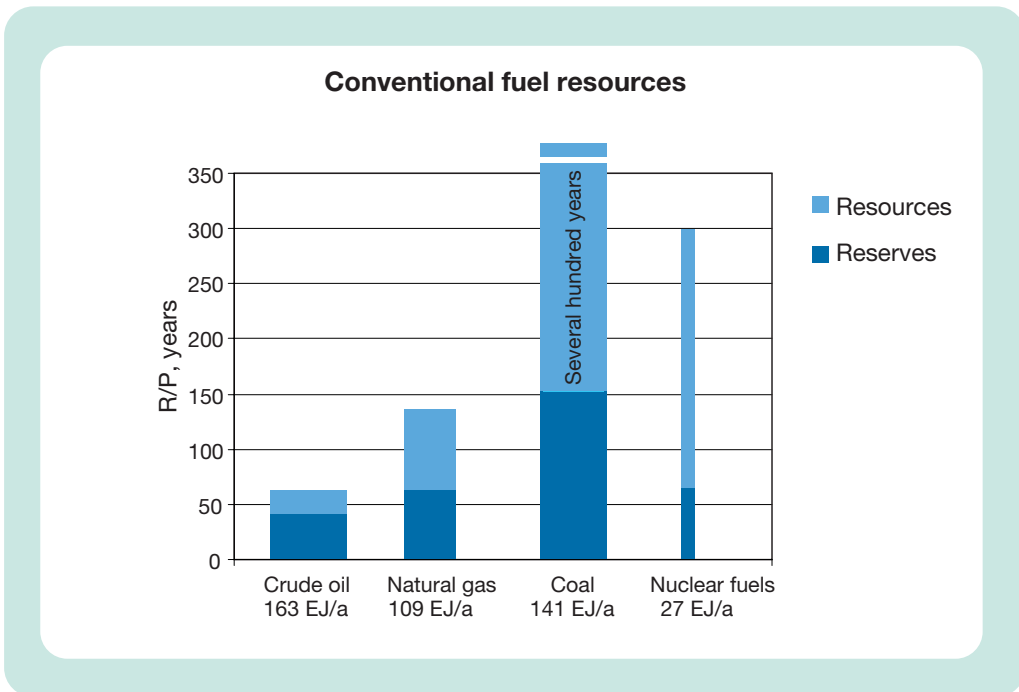


Figure 12. Sufficiency of conventional fossil fuel and uranium resources at today's consumption levels and technology. The width of the histograms indicates the current consumption level and the area indicates the size of each resource in energy terms (Data source: BGR 2006). Many renewable resources not presented in the figure have theoretical and technical potential to meet the world's energy demand many times over. Furthermore, advanced nuclear power technology concepts of the future have the potential to increase the resource sufficiency by orders of magnitude.

energy has the theoretical potential to cover a large part of the increased energy needs of Mankind. Of the renewable energy sources, geothermal energy also has large theoretical potential. However, the technical potential for solar and geothermal resources is much

smaller than the theoretical potential.

About 1 - 2% of the energy in the atmosphere is converted into wind. Assuming current technology, the technical potential for global wind power production is estimated to be approximately 1,000 PWh/a (3,600

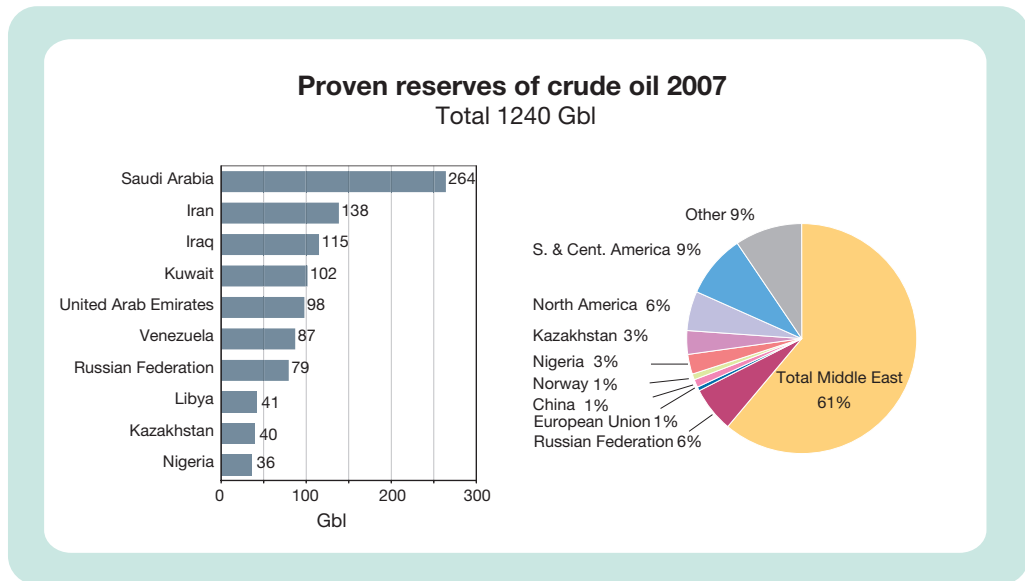


FIGURE 13. Proven reserves of crude oil 2007 (1 GBl = $1.36 \cdot 10^8$ tonnes (metric)). (Data source: BP 2008)

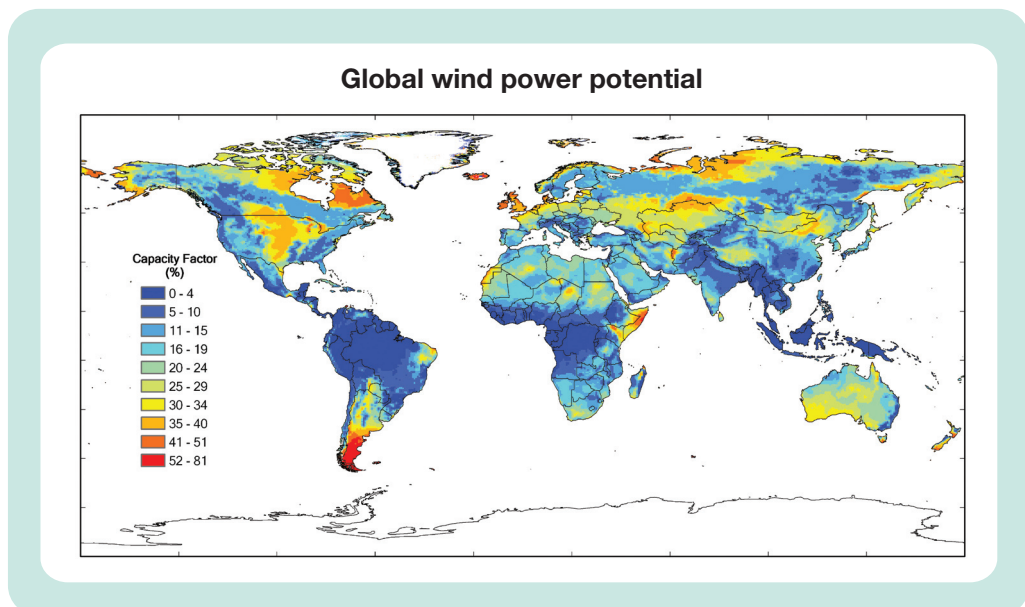


FIGURE 14. Global wind power potential in terms of capacity factor. The bigger the capacity factor, the more beneficial the wind power resources at a location. (Lu, McElroy & Kiviluoma 2009)

EJ/a). This includes offshore resources in regions situated not too far from the mainland and at decent water depths, although the main part of the estimated resource is onshore.

The geographical distribution of the onshore wind resource can be seen from Figure 14. Current global resource maps are indicative only, as the resolution and quality of the data is not high enough to make good estimates. The low resolution of the data means that some areas, especially where the terrain is complex, are not presented correctly. However, a comparison with high-resolution wind atlases indicates reasonable agreement with Figure 14.

Current usage of biomass is concentrated in the developing countries. The developing countries as a whole derive 33% of their energy from biomass, used mostly as traditional fuel for cooking and heating. An assessment of the future potential of biomass-

based energy needs to take into account other land uses, such as food production, biodiversity, soil and nature conservation, as well as carbon sequestration. This question determines its feasibility for climate change mitigation and other challenges in the energy sector. A recent study by VTT and MTT Agrifood Research Finland resulted in a range of 120-210 EJ for the potential of biomass-based energy in 2050 under different scenarios (Koljonen et al. 2009; Pahkala et al. 2009, see Figure 15). The range is due to different assumptions about factors such as land use and food production. The lower limit of the biomass potential represents a scenario where the emphasis in food production is on a meat diet, whereas the upper limit represents the potential when a vegetarian diet is more favoured.

Of the different types of nuclear energy, fusion energy aims to harness the same type of fusion reactions that form the basis for

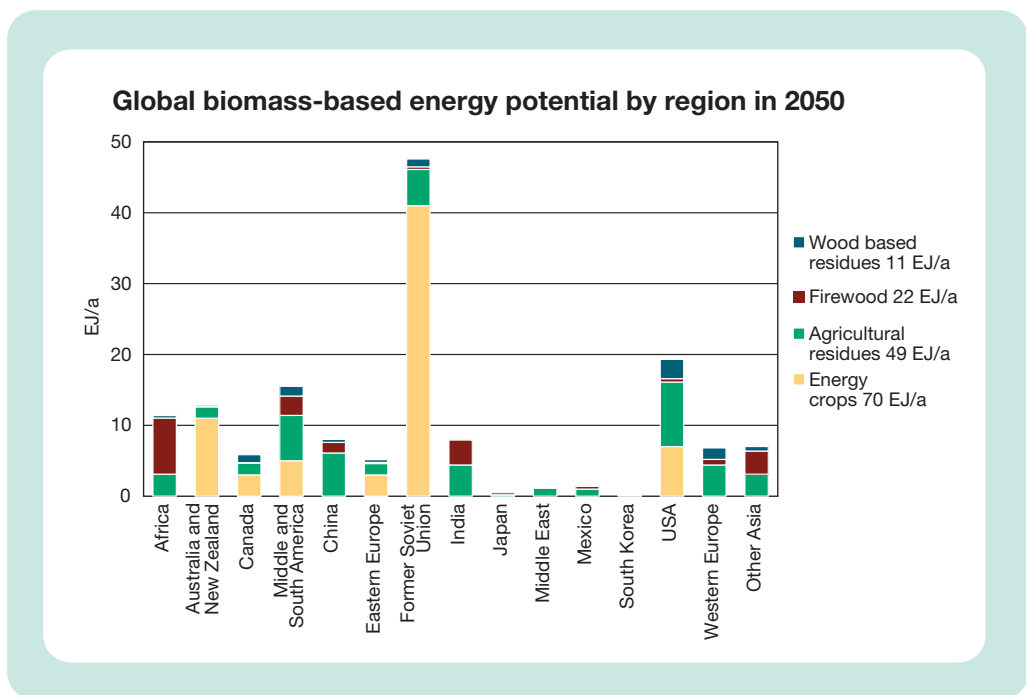


FIGURE 15. Biomass energy potential (EJ/a) in different regions of the world, derived from VTT's analysis of wood-based energy potentials and MTT's estimation of agricultural residues and main energy crops (Koljonen et al. 2009; Pahkala et al. 2009).

Vision box: photosynthetic microbes as a future source of energy

In principal, all photosynthetic organisms can be viewed as sunlight-driven cell factories that convert CO₂ into organic molecules with biofuel potential. It has been estimated that on an areal basis the productivity (the yield per unit area) of photosynthetic microbes (PMs), i.e. microalgae *sensu stricto* comprising prokaryotic cyanobacteria and eukaryotic 'true' algae, exceeds that of terrestrial plants by at least one order of magnitude. However, there is huge variation among species concerning the lipid content they can reach under specific conditions. The biodiversity of PMs is estimated to exceed 100,000 species, but only about 40,000 species have been identified so far, and of these only a few species have been investigated in terms of their potential regarding biofuel production. Nevertheless, oil contents of between 20 and 70% dry weight have been reported and rather conservative calculations foresee yields starting at 58,700 l/ha (Chisti 2007). By comparison, the yield per unit area of *Jatropha*, an emerging oil plant in the sub-tropics and tropics, which could ease the pressure on arable land because it can be grown on marginal land, is 1,900 l/ha/year. That is too low to allow the replacement of current fuel sources as it would require 17% of the global landmass. These figures illustrate the enormous potential of PMs, theoretically allowing TW output to make a significant contribution to future fuel demand.

Technologies that provide practical solutions, including cultivation and processing for the mass production of PMs at the scale required, are currently immature. Only four species exhibiting very specific growth requirements have been cultivated on an industrial scale, but only for the production of food supplements and fine chemicals. Earlier massive research programmes, like the US Aquatic Species Program (ASP) that focused on open pond cultivation (1,000 m²), came to the conclusion that monospecific cultures cannot be maintained in a sustainable way for more than a few months due to contamination. On the other hand, the Japanese 'Research Institute of Innovative Technology for the Earth' (RITE), which concentrated entirely on the use and development of photobioreactors, did not reach an industrial scale (Lee 2001). Photobioreactors are different types of closed systems with transparent walls or fibres for light supply, which enable exact growth control via nutrient and CO₂ dosage. A pragmatic solution that maintains a balance between high costs and simplicity might be a two-stage approach involving the combination of a photobioreactor for axenic feeder production and outdoor ponds for final upscale. Success using this strategy, i.e. combining 25,000 l) photobioreactors and 50,000 l) open ponds, has been reported from a commercial operation in Hawaii producing carotenoids in *Haematococcus*. For temperate regions with changing seasonal light levels, convincing concepts have not yet been presented. Potential solutions might be the switch to mixotrophic or heterotrophic growth modes, which would necessitate additional carbon sources that are different from CO₂, e.g. from waste water streams.

Apart from the technical and economic problems in photobioreactor design suitable for large-scale use, there are additional difficulties in biomass recovery and further downstream processing (Molina Grima et al. 2003). Specifically, the biomass has to be recovered from relatively dilute (<0,5 kg m⁻³) culture broths, avoiding energy-demanding methods, such as centrifugation, for example. Suggested methods include filtration, which can be problematic due to the small size (3-30 µm) of algal cells, and flocculation, which could at least be utilised to aggregate cells in order to sediment or filter them more easily.

Ultimately, the whole value chain of PM-derived biomass has to be evaluated in order to overcome currently limiting economic constraints. The biorefinery concept (cf. scheme) fully integrates chemicals and energy chains. The remaining biomass, after lipid extraction, can be utilised in different ways, such as microbial conversion to methane, hydrogen, ethanol, lipids or electricity. Additionally, chemical compounds can be extracted as valuable by-products, further benefiting the overall economics of the process.

Apart from the selection of suitable species as mentioned above, genetic engineering of PMs could help to finally achieve the economical production of biofuel. Photosynthetic efficiency, growth and yield are obvious traits for optimisation. At the moment, however, only a few algal genomes have been sequenced and annotated. More research is needed towards generating a solid knowledge base on algae and for the development of molecular tools for genetic modification. At the same time, biosafety needs to be examined in order to minimise environmental risks.

solar energy. Nuclear fission energy is based on splitting some of the heaviest elements, such as uranium and thorium. These have few other uses, and nuclear fission can be an abundant energy source if advanced technological concepts are employed to improve the efficiency of the usage of these resources. This effect is illustrated in Figure 16, which presents estimates of resource availability assuming different nuclear fission reactor technologies

ENERGY SUPPLY SYSTEMS

A system for providing energy in a useful form to end-users primarily consists of an energy source, transportation (or distribution) and, in many cases, storage, energy conversion and end-use. Since the storage of energy in some forms is currently economically or technically unfeasible in present energy systems, energy is often stored in the form of the primary energy source, such as coal, oil, natural gas, etc., and production is matched with momentary

demand.

Energy Visions 2050 is primarily concerned with energy supply systems that have an established and wide-spread infrastructure, i.e. electricity and district heat supply systems. In a longer timeframe, beyond 2050, the hydrogen economy, including all the necessary the infrastructure, could provide a versatile new energy carrier for the storage or transportation of energy.

Electricity supply systems include, in addition to power plants, high-voltage power grids and distribution networks. Nowadays, the power network is integrated with telecommunication and telecontrol systems in order to ensure safe and reliable operation of the electrical power system. In the future, the large penetration of distributed generation (i.e. producing energy from small local energy sources), renewable energy sources, demand-side management and energy storages will partially displace energy produced by large conventional plants. Distributed generation will have particular significance in developing countries, where electricity supply systems are often limited.

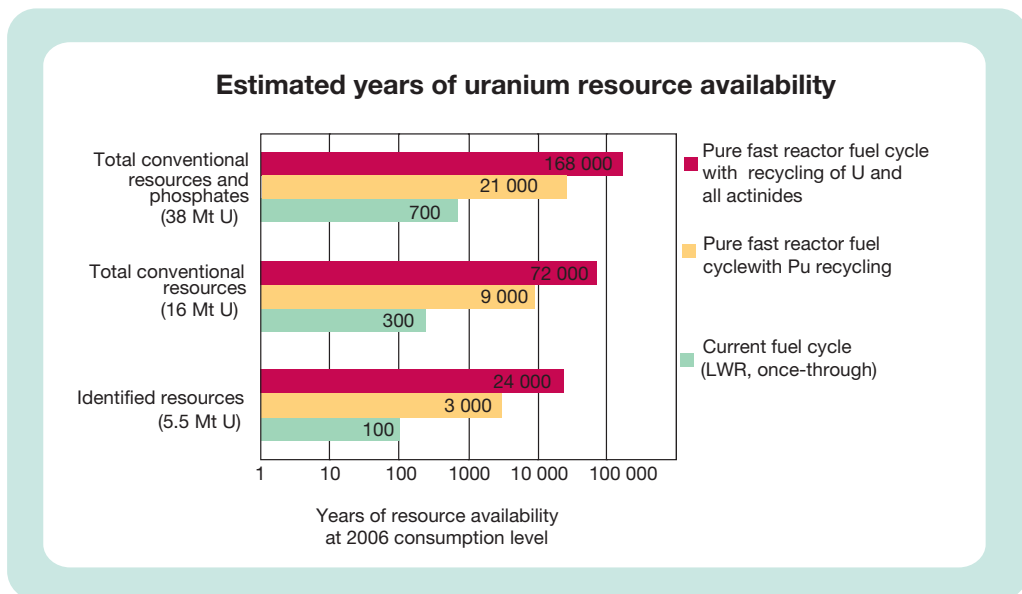


FIGURE 16. Estimated years of uranium resource availability for various nuclear technologies at the 2006 level of nuclear power utilisation (2,660 TWh/a; 29 EJ/a). (Data sources: OECD 2008; OECD 2001; OECD 2006)

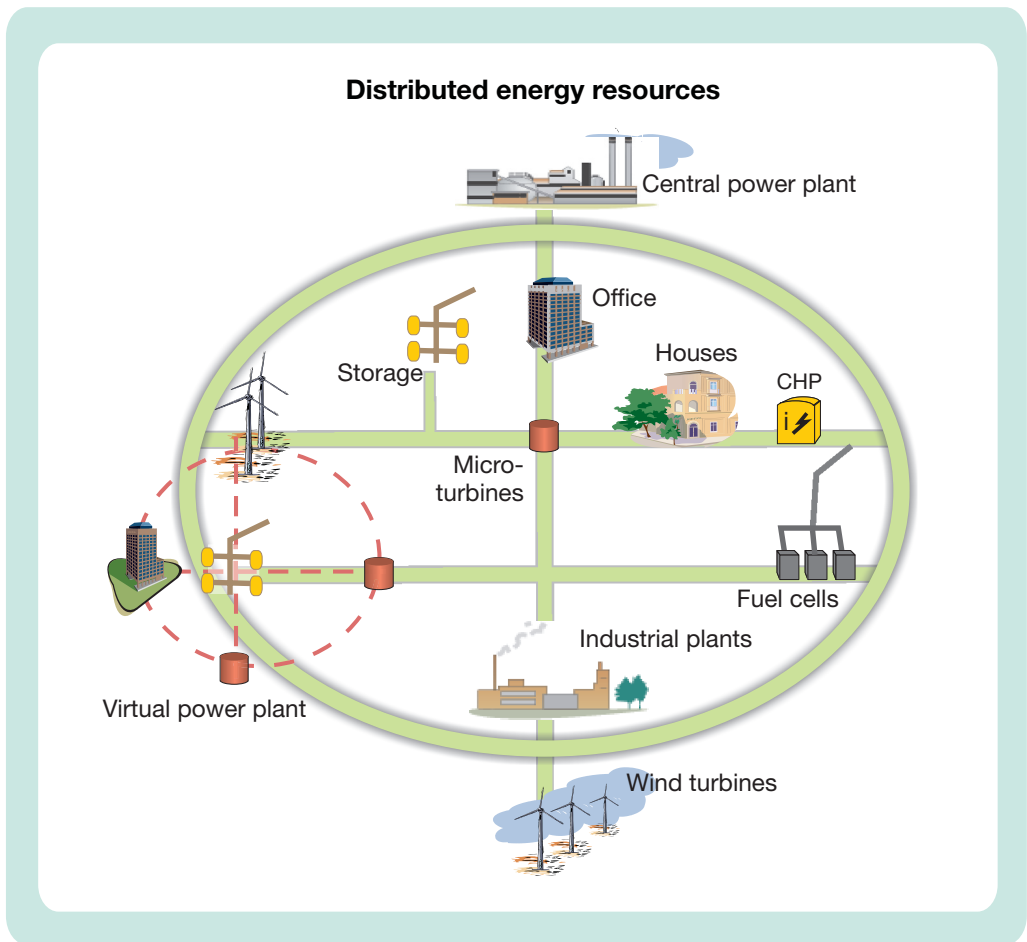


FIGURE 17. Balance between different energy sources in the future.

The function of an active distribution network is to efficiently link the sources of power with consumer demands, allowing both to decide how best to operate in real time. Enabled by smart metering, modern communications and the increased awareness of customers, energy management will play a key part in establishing new services that will create value to the parties involved. In the longer term, a super power grid across regions/countries utilising advanced technology presents a conceivable opportunity.

District heating is presently applied in Europe, Northern America and Asia. Consumption in the EU27 countries is about

10% of the total heating demand. In the USA, about 4% of house heating is produced by district heating. Finland is a forerunner in district heating: about half of the building stock is nowadays connected to district heating. The proportion is more than 90% in the largest cities. The large penetration rate has contributed to Finland's internationally high share of efficient combined heat and power (CHP) production. More than 75% of district heating in Finland is produced by combined heat and power.

In the future, a district heating system must be adapted to low-energy systems in buildings or even heat producer (energy positive) buildings. A heat trading system

like the present electricity trade in the EU countries is needed in regional heating systems. Because of low-energy buildings, higher buildings will be needed in towns and cities, and higher density building plans will be needed in the suburbs. Future district heating systems could be operated at a lower temperature (60 °C) than nowadays (80 – 120 °C). This also makes it possible to plan new types of CHP plants with higher power-to-heat ratios, which better correspond to society's energy consumption structure.

Hydrogen is seen as a viable possibility for alternative energy carriers because it is clean in use with the only emission being water. Hydrogen has a large energy content per unit mass and it can be stored. However, it has one drawback. In its gaseous form, it has a low density and, therefore, storage and

transportation creates some challenges.

Like electricity, hydrogen can be produced by a number of technologies using several primary energy sources, many of which are renewable. Carbon-lean technologies, electrolysis using nuclear electricity and gasification of biomass are proposed as the technologies for producing the bulk of the hydrogen.

The hydrogen economy, including all the necessary infrastructure, could provide a versatile new energy carrier for the storage or transportation of energy. The ultimate goal is that all hydrogen will be produced from carbon-lean energy sources, i.e. renewable sources, nuclear fission and, perhaps, fusion after 2100. Hydrogen is estimated to be used mainly as a transport fuel and also as an energy storage medium to balance power production and demand.

Vision box: Multiple energy carrier system

The electricity, natural gas, and district heating/cooling infrastructures operate almost independently nowadays. A number of benefits can be achieved by combining these systems and taking advantage of their specific virtues. Electricity can be transmitted over long distances with low losses. Chemical energy, such as natural gas, can be stored using simple and cheap technologies. Compressible fluids can be stored in pipeline networks without different storage devices.

Combining the infrastructures means coupling them, thereby enabling the exchange of power among them. Couplings are established by converter devices that transform power into other forms. For this purpose, an energy hub is considered. This is a unit where multiple energy carriers can be converted, conditioned, and stored. It represents an interface between different energy infrastructures and /or loads. Energy hubs consume power at their input ports, which are connected to, e.g. electricity and natural gas infrastructures, and provide certain required energy services, such as electricity, heating, cooling, and compressed air at their output ports. It is also possible to convert and condition energy using, e.g. combined heat and power technology, transformers, power-electronic devices, compressors, heat exchangers, and other equipment.

For energy transmission purposes, an energy interconnector is proposed that will enable the integrated transportation of electrical, chemical, and thermal energy in one underground device. So far, the most promising layout seems to be a hollow electrical conductor carrying a gaseous medium. Concepts involving liquid chemical carriers or other forms of energy may be advantageous as well. The time horizon for the implementation of multiple energy carrier systems is set at 30–50 years from now.

Sources: Geidl et al. 2007; Favre-Perrod & Bitschi 2006

SCENARIOS ON ENERGY FUTURES

Scenarios for the development of the energy systems and greenhouse gas emissions in the long-term future – to 2050 and beyond – have been constructed in the Energy Visions 2050 book. They are obtained from model calculations, assuming different global economic development, information and capital flows and technology development. Among other things, estimates of costs to achieve the emissions reduction targets and their impact on energy systems in the future are obtained from the results from global, European and Finnish perspectives. The long-term energy and emission scenarios presented illustrate that through profound technological progress and international agreement to tackle climate change, a sustainable energy future is possible.

Energy system scenarios have been created using the global TIAM model (TIMES Integrated Assessment Model) at VTT. In addition to comprehensive technology characterisations, the energy system model also

includes basically all sources of anthropogenic global greenhouse gas emissions as well as a simplified climate model. In order to develop consistent long-term energy scenarios, world-wide economy simulations have been carried out in the project using the database and models of the Global Trade Analysis Project (GTAP) at VATT. The GTAP simulations provide projections of the development of global and regional economies and sectoral outputs, which are used as inputs in the TIAM model.

The scenarios presenting global (and European) energy system results are called ‘Baseline’, ‘2 °C Market’, ‘2 °C Boosted’ and ‘Regional world’. The ‘Baseline’ scenario features a continuation of the trends and policies prevailing before the entry into force of the Kyoto protocol in 2005. No international agreements on climate change policies are assumed.

In the ‘2 °C Market’ and ‘2 °C Boosted’ scenarios, global greenhouse gas emissions are simultaneously optimised to achieve the 2°C limit on global warming by the year 2100. Global markets for greenhouse gas

TABLE 2. Basic characteristics of the scenarios considered.

Characteristic	Baseline	2°C Market	2°C Boosted	Regional world
Development of economy	Globalisation	Globalisation	Globalisation	Regional policies
Costs and potential of new technologies	Moderate development	Moderate development	Boosted development	Moderate development
Level of required return on energy efficiency investments	Moderate	Moderate	Low	Moderate
GHG emission reduction objective	None	2°C warming limit	2°C warming limit	Regional emission targets

emissions are assumed, featuring continued globalisation. Thus, according to the model results, the globally optimum solution to achieve the 2 °C warming limit is obtained. The '2 °C Boosted' scenario further assumes boosted research and development on energy technologies as well as increased sustainability awareness. These features are reflected in the more rapid development and deployment of new technologies, causing their investment costs to decrease more steeply.

The 'Regional world' scenario features development towards a more protectionist world, assuming regional policies obstructing globalisation and thus reduced market openness. The basic characteristics of the scenarios are summarised in Table 2.

For the global energy system scenarios, two different scenarios of economic development have been constructed by VATT: a 'Baseline' scenario featuring continued globalisation, and a 'Regional world' sce-

nario featuring a rise in more protectionist and nationalist agendas. In the results of the world economy simulations, the most striking difference between the 'Baseline' and 'Regional world' scenarios is in the structures of regional economies. In the 'Regional world' scenario, the global output value of all industries in 2050 is only 2–3% below the level of the 'Baseline'. However, the distribution of this output between sectors is different. According to the results, the transition towards a modern economy is slower when protectionist and nationalist agendas arise. This is seen in the fastest growing regions, where the development of traditional industries has taken place to a greater extent than, e.g., services. Figure 18 shows the effect in the structure of economies; one can see that industrial output is skewed towards energy-intensive industries in the 'Regional world' scenario, compared to the baseline scenario.

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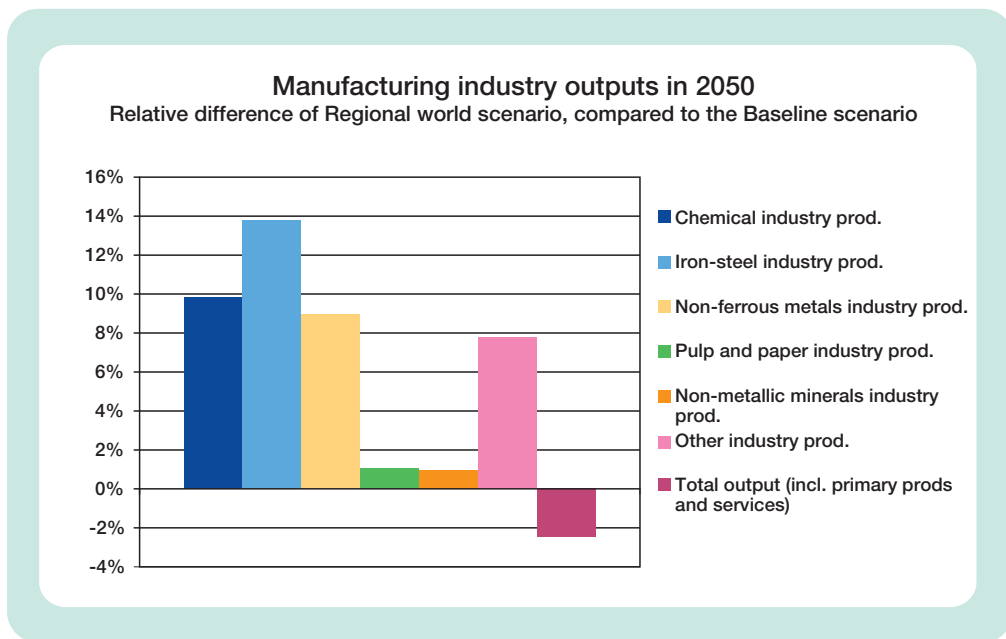


FIGURE 18. An example of the results of global economy simulations: manufacturing industry outputs in 2050 in global economy simulations, relative difference of 'Regional world' scenario, compared to the Baseline scenario. One can see that in the 'Regional world' scenario, industrial output is skewed towards energy-intensive industries, e.g. chemical, iron and steel, and metal industries.

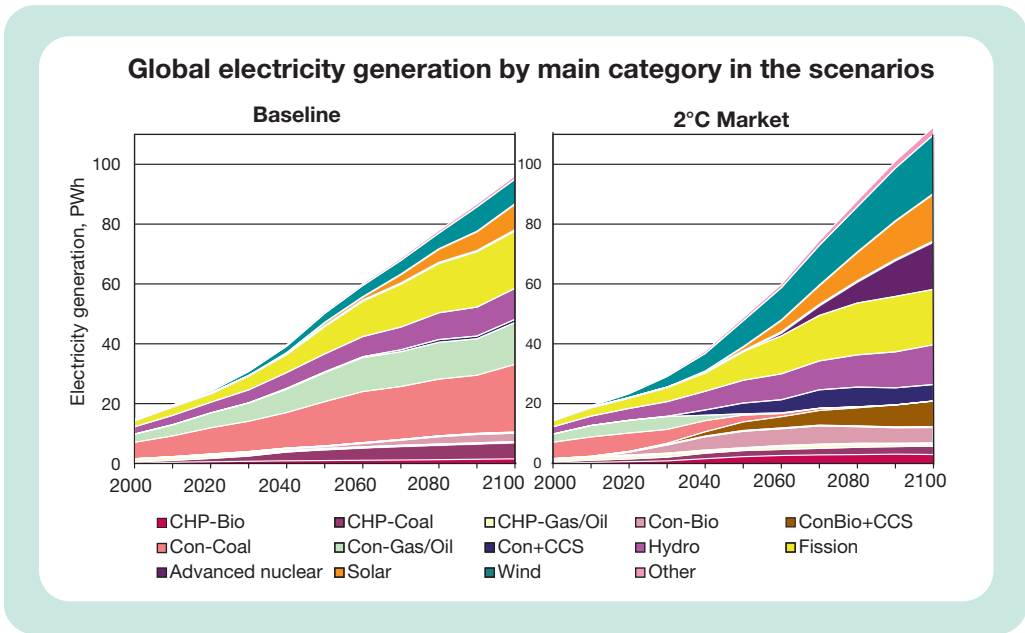


FIGURE 19. Global electricity generation by main category in the 'Baseline' scenario and in the '2 °C Market' mitigation scenario, which optimises the energy supply achieving the 2 °C warming limit. By comparing the figures, one can clearly see the difference in the structure of electricity generation implied by climate change mitigation. A wide variety of technology options are needed for tackling climate change.

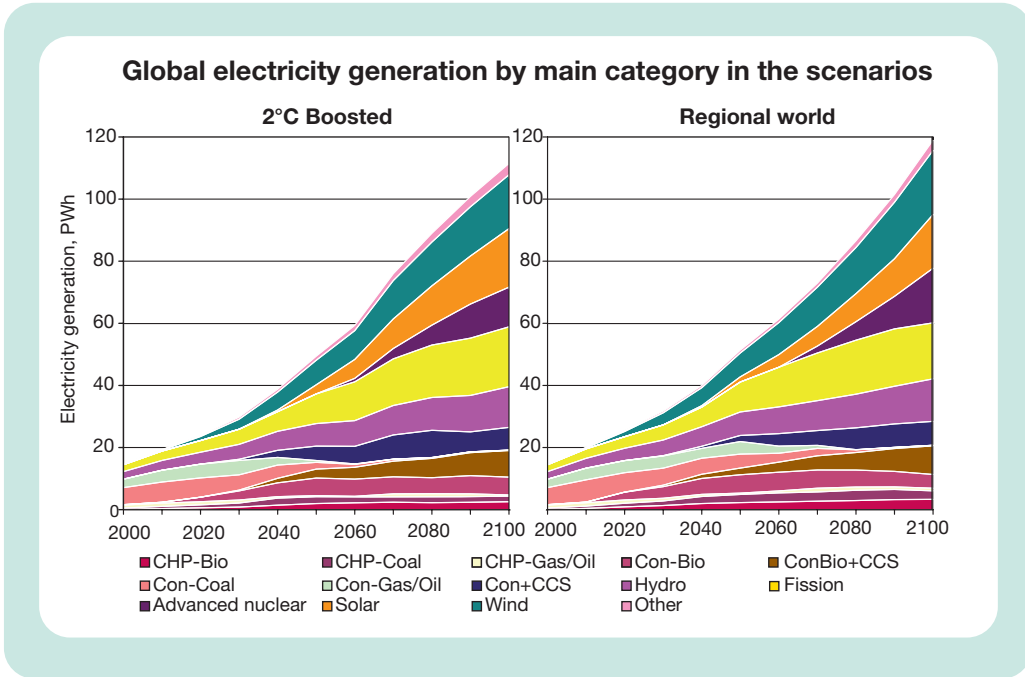


FIGURE 20. Global electricity generation by main category, '2°C Boosted' and 'Regional world' mitigation scenarios. Boosted R&D&D accelerates technology penetration but the key technologies may remain the same. Regional policies tend to increase energy consumption.

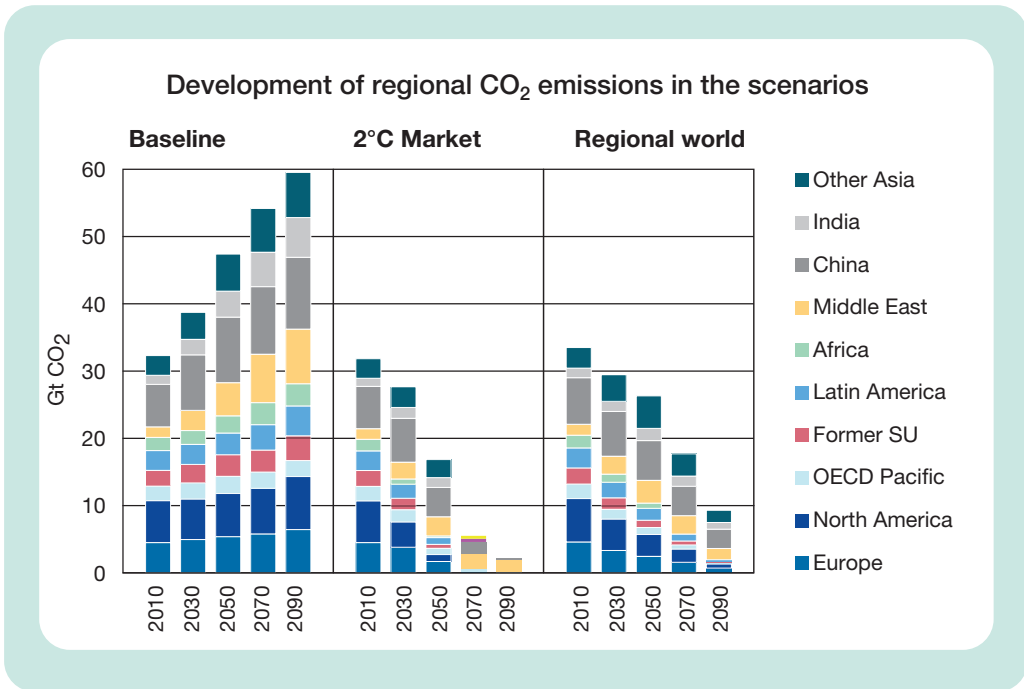


FIGURE 21. Development of regional CO₂ emissions in three scenarios. One can see the smaller emission reductions in the 'Regional world' scenario than in the '2°C Market' scenario. According to the results, this implies greater warming of the climate. OECD countries should reach almost zero net emissions by 2070 under the 2°C target.

2050, in the summer of 2009, the world is facing an economic recession. In these economic conditions, there has been increasing discussion on policy changes that could make 'Regional world'-like scenarios more realistic.

According to the results of the scenarios aimed at climate change mitigation, the average final energy intensity of the global economy should decrease by over 2% annually in order to limit the increase in the global mean temperature to at most 2°C within this century. Such a decrease would be much more rapid compared to the average improvements of 1.1% between 1990 and 2005. The most significant technological shifts would, however, have to take place in energy production. Up to the year 2050, wind turbines, nuclear power, biomass-based electricity generation and power plants equipped with carbon capture and storage will all have a very important

role in achieving a more sustainable global energy system. Solar energy also has huge potential, but the costs of solar technologies would have to decrease quite steeply in order to reach a significant market share in power generation before 2050.

Very large investments in new energy technology are needed by 2050 on the path to more sustainable energy use. In the electricity sector alone the global annual capital expenditures related to new plant investments would reach about €1,400 billion and the investments in more efficient technologies would be high also in all end-use sectors. Although the financing of the investments would be challenging, the investment requirements would also create enormous market opportunities for both technology developers and producers.

Figure 22 shows the investments needed for selected technology groups in power and heat generation in the 2°C Market scenario.

While in the baseline scenario the use of fossil fuels, especially coal, increases rapidly, in the 2°C policy scenarios renewables and nuclear dominate. The annual capital expenditures in 2050 for both wind power and biomass-fired power were each almost €300 billion per year. For electricity production with CCS the calculated annual investments in 2050 were around €250 billion per year. It should also be noted that global capital expenditures for both nuclear power and hydro power would be very significant and strongly increase between 2020 and 2050. However, both nuclear and large-scale hydro power investments are usually regulated by national policies, which could prohibit these investments in the future.

The scenarios for the Finnish energy system (Lehtilä et al. 2008) indicate that the key technologies fall into the same categories in Finland as well. Both nuclear power and wind power appear to have great economic potential under strict climate policies.

Moreover, the use of biomass for energy can still be substantially expanded in Finland, not only through the more enhanced use of forest residues, but also by utilising the surplus in forest growth and through agro-biomass production. Achieving a completely carbon-free electricity system nevertheless appears to be a very challenging target by 2050. Moreover, particularly with respect to the transportation sector, the technological challenges are global, and domestic measures have rather limited potential.

Conclusions

There is a wide variety of technical solutions that can be used to improve overall energy efficiency and reduce energy-related emissions. With regard to energy production technologies, many advanced technologies based on emission-free energy sources or very low-emission technologies are currently being actively developed. Many

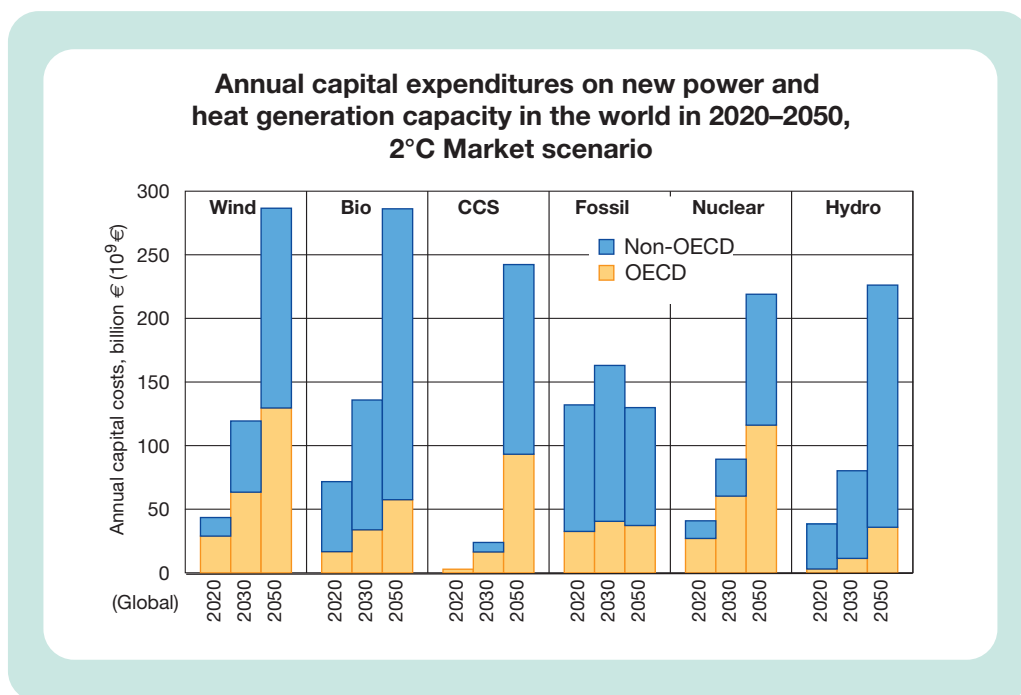


FIGURE 22. Annual capital expenditures on new power and heat generation capacity in 2020–2050, 2°C Market scenario.

of these technologies have either not yet been commercialised, or are still in the initial stages of market entry. *Energy Visions 2050* introduces numerous examples of such advanced energy production technologies for the future. Concerning the end-use of energy, in the very long term, remarkably large improvements may be achieved in the energy efficiency of many end-use applications. Due to the inherent inertia of energy systems, in the short term, large improvements through rapid shifts in technology might be quite costly. However, gradually over time, the full technical potential can be expected to become more or less fully commercialised.

Even though addressing the climate change issue appears to require large changes within the next 40 years, in the longer term, technology development may open up yet more sustainable energy options. Gradually, various solar energy technologies will inevitably become much more competitive, and may well have a very significant role by 2100. In addition, advanced nuclear technologies, including nuclear fusion, may acquire a key role in carbon-free

hydrogen production, thereby contributing to the ultimate phasing out of fossil fuels.

The challenges related to the mitigation of climate change, access to energy and energy security will require huge investments in the system of energy production and use in the future. There is plenty of room for new innovations and markets for more efficient technologies. This can offer a base for new industries designing and manufacturing technologies and offering services and maintenance.

The uncertainty surrounding the long-term development - dozens of years ahead - is naturally high. In the coming decades new technological developments in fields such as ICT, nanotechnologies and materials science may improve energy efficiency considerably and offer opportunities that are beyond our present-day understanding. New innovations and technological development as well as the development of the economic framework are very difficult to predict, so actual development in the coming decades may be very different from the scenarios presented in this book.

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energy visions 2050



Summary

Radical greenhouse gas emission reductions are needed in order to mitigate climate change. The energy sector is the main source of greenhouse gases, so revolutionary changes in the global energy system, which today is mainly based on fossil fuels, are essential. Global energy demand is forecast to continue growing in the coming decades, especially in the developing economies. This growing demand, accompanied by depleting and geographically concentrated fossil fuel resources, will highlight the importance of energy security in the future.

Energy Visions 2050 considers measures for addressing the enormous future challenges facing the energy sector, focusing on technological and techno-economic perspectives. The topics are approached from a global perspective. In some technological details, however, Finnish technology and Finland's technological achievements are highlighted. This summary presents highlights and key messages of the results of the book. The analysis of the development of technologies covers the whole energy chain, highlighting the necessity of efficient energy use in all activities of societies. The contents include a discussion on potential future low-emission and renewable energy conversion technologies, as well as new technology solutions in the industrial, building and transport sectors and in energy supply systems. The move towards zero-emission energy systems has consequences for energy supply, and makes the analysis of energy resources presented in the book all the more valuable.

Scenarios of alternative development paths to 2050 are presented, assuming different technological development options, economic growth rates, degrees of globalisation and information flows. The results show interesting differences between the scenarios with regard to energy production and use, mitigation of greenhouse gas emissions, and global warming.