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A sustainable energy system in 2050: promise or possibility?

A vision by ECN and NRG

October 2007

ECN and NRG's energy vision

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Abstract

Energy policy is facing major challenges. Industrial countries are increasingly dependent on imports of oil and gas, and global warming is becoming more of a reality. In order to address these challenges, a sustainable energy system must be developed. This document presents an outline of a sustainable energy situation for Europe in the year 2050. The research institutes ECN and NRG hope that this vision will guide energy research and inspire both businesses and governments.

The authors describe a consistent development path that leads to a reduction in CO_2 emissions in Europe to 60% below 1990 levels, and to a significantly reduced level of oil and gas imports. However, in 2050 the energy system will not be completely sustainable. The authors have formulated additional sustainability conditions for the reliable use of nuclear energy, biomass, and CO_2 capture & storage in a sustainable energy system. If these conditions are complied with, the overall picture will meet realistic criteria of sustainability. Despite this, continued energy conservation and further development of renewables should be pursued after 2050.

In the vision for 2050 presented here, much weight is given to new technologies, new resources and new energy infrastructure. In addition to such innovation, new ways of decision-making and new patterns of behaviour are essential. With respect to technological developments that result in, for instance, affordable solar cells, the deployment of second-generation biofuels and reliable CO_2 capture & storage, realistic judgements have been made as to the timing of their commercialisation. The technology policy required to bring about such technological developments is briefly outlined.

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Summary

Energy policy is facing major challenges. Industrialised countries are increasingly dependent on imports of oil and natural gas, while global warming continues. It is imperative to develop a sustainable energy system in order to combat this situation. This document outlines a vision of a more sustainable energy system for the year 2050. The research institutes ECN and NRG have developed this vision to guide energy research and as a source of inspiration for both the private and the public sector.

The vision is that, by 2050, renewable energy sources will account for more than 35% of the total energy supply, with biomass, wind and solar energy taking leading roles. Considerable attention will be paid to energy conservation. Nuclear energy will have a limited role, as only half of the EU Member States will support the use of nuclear energy. Coal with CO_2 capture will be applied on a large scale for the production of both electricity and hydrogen. The hydrogen will be used in the transport sector. Biomass will primarily be used as fuel for freight transport, and as feedstock in industry, as there are few other substitutes for oil products in these sectors. The energy needs of dwellings and other buildings will have been greatly reduced, and will primarily be met with solar energy and electricity.

The authors have attempted to map out a consistent development path that leads to a reduction in CO_2 emissions in Europe to 60% below 1990 levels, as well as to a significant decrease in oil and natural gas imports. The energy system will not be fully sustainable by 2050: there will still be opportunities for further energy savings and it will be necessary to develop renewable energy sources further. However, the major problems of the current energy system will have been overcome.

Achieving a sustainable energy supply requires a consistent and effective policy that promotes close cooperation between governments, businesses and citizens. Due to the inertia of the energy system, and the time required for technologies to sufficiently mature and become competitive, it is imperative to set out on this policy in time. It is also important that the private sector can operate within a clear and stable policy framework that provides reliable pricing signals.

The vision for 2050 is centred on the application of new technologies, new energy sources and a new energy infrastructure. However, these changes will be successful only if they are combined with new organisational forms and changes in behaviour patterns. Realistic time-to-market projections have been drawn up concerning such technological innovations as the development of affordable solar cells, the availability of second-generation biofuels and the reliable capture & storage of CO_2. An analysis is presented of what is needed to promote such technological advances. A calculation model has been used to provide a quantitative foundation for the developments described.

Not all energy sources in use by 2050 will be fully sustainable. Conditions have to be formulated particularly for nuclear energy, biomass and CO_2 storage in order to guarantee their responsible use as part of a sustainable energy system. If these conditions are complied with, we will meet realistic and achievable standards of sustainability.
No single option should be excluded prematurely, considering the size of the challenges to be met.

Foreword

It is 30 September 2050. Climate change first started to receive attention during the 1990s. At that time, growing numbers of scientists began to establish and reveal the connection between increased concentrations of greenhouse gases and climate change.

This finding was both new and somewhat controversial, and policy makers were slow to react. The first global agreement on the emission of greenhouse gases – the Kyoto Protocol – was reached in 1997. The aim of the Protocol is to reduce emissions to 5% below 1990 levels by 2010. However, the agreement was not ratified by the United States, Australia or the larger developing countries.

The Kyoto Protocol was no more than a beginning, a tiny step that, as such, would have had little effect on climate change. However, even though it was not a great leap forward, it was a significant indication of a change in attitudes. The Protocol did not lead to major changes in the energy system, although a limited number of European countries did take a few measures related to wind energy and energy conservation. Among the reasons for the lack of action were the extremely low prices of oil and natural gas, and little concern about their supply. In addition, many people believed that climate change would not turn out to be a real problem.

Climate policy finally began to pick up pace in 2007 as a result of a series of events: in 2005, the USA had been struck by an unprecedented number of hurricanes, new insights had been gained into the magnitude of the economic effects of climate change, 2006 had been an extremely hot year, and former US vice-president Al Gore released an alarming documentary about climate change. In addition, concern arose about the availability and pricing of oil and gas: the price of oil had risen from $20 to $70 a barrel in just a couple of years, and the Russian president had embarked upon an energy-driven policy of power play by cutting off or threatening to cut off supplies of gas to certain countries, and by discouraging foreign investors. China and India were becoming economic heavyweights and were consuming large, and increasing, amounts of energy. Fortunately, businesses began to develop a practical implementation of socially acceptable business practices. The impact of new products and investments on energy consumption and the climate increasingly became a factor to be taken into account.

In Europe, we became aware that if we did not take action we would become increasingly dependent on imports of oil, gas and coal, and that this supply would become increasingly unstable. Moreover, only a limited number of European countries considered nuclear power to be an option. We realised that Europe should not simply follow others but take the initiative in combating climate change. We hoped that other regions around the world would follow, as their effort is essential in addressing the problem. At the time, we could not yet know that they would follow.

We hope that this document will inspire you.

1. Introduction

The current energy system is not functioning well. Industrialised countries are increasingly dependent on imports of oil and natural gas, while global warming continues. Both businesses and consumers are aware of this situation, but are reluctant to change their behaviour. Therefore, governments must take the initiative. Although there is a certain amount of energy policy aimed at energy savings and sustainability in the Netherlands and other European countries, it is focused on limited, short-term changes. In order to decrease the severity of the dangers posed by climate change and to guarantee the long-term supply of energy, we need to implement radical changes to our energy system. A dramatic reduction of CO_2 emissions must have the highest priority. The European Commission seems to have embraced this idea and the current Dutch government has developed its own set of policy targets. Most energy users, however, are not yet aware of what all this will entail in practice.

There is a need for an integrated vision concerning energy supply in 2050, as such a vision could give direction to the plans of businesses, researchers and policy makers. Although this need is both urgent and obvious, it has not been fulfilled.

ECN and NRG are research institutes that focus on the development and implementation of high-level knowledge and technology for a sustainable energy system. The institutes consider it important to have a clear vision of a more sustainable energy system in 2050, as this could lead to better guidance of choices concerning energy research. Such a vision of a more sustainable energy system can also be a source of inspiration for both businesses and governments.

The vision presented in this document has a European scale, as energy production and transport are strongly interwoven between European

countries and because Europe is increasingly acting as a single entity. Plans for energy policy, climate policy, R&D policy and innovation policy are increasingly being developed in a European context. We chose the year 2050 as, given the long lifetime of much energy infrastructure, the timescale allows for radical changes to the energy system. The vision is that a reduction of CO_2 emissions to 60% below 1990 levels is achieved by 2050. If this goal is indeed achieved, and if other regions of the world take similar steps, the warming of our planet will be limited to approximately 2° Celsius – the consequences of which, according to contemporary consensus, will still be more or less manageable. The vision includes a reduction of oil and gas imports. The authors have attempted to provide a vision that is practical, based on realistic yet ambitious developments in technology and on the behaviour of businesses and consumers. The vision was developed by a project team that has an understanding of energy supply, new technologies and the effects of policy decisions. They have analysed the vision using an integrated energy model to check for inconsistencies. The vision is dominated by new technologies, new sources of energy and new energy infrastructures, as these are the areas in which most sustainability can be achieved. However, new forms of organisation and new habits will have to play an equally important role.

ECN and NRG are aware that future developments cannot be predicted with precision. The projections of technological developments have been well-researched, but in practice there will always be both windfalls and disappointments. The researchers believe that these eventualities will largely cancel each other out, and that most of the presented changes will prove to be accurate. This vision must not be seen as a conclusion to the debate, but rather as an intermediate stage: it is important to reassess the situation every five years or so in the light of new developments. Reactions to this vision are most welcome.

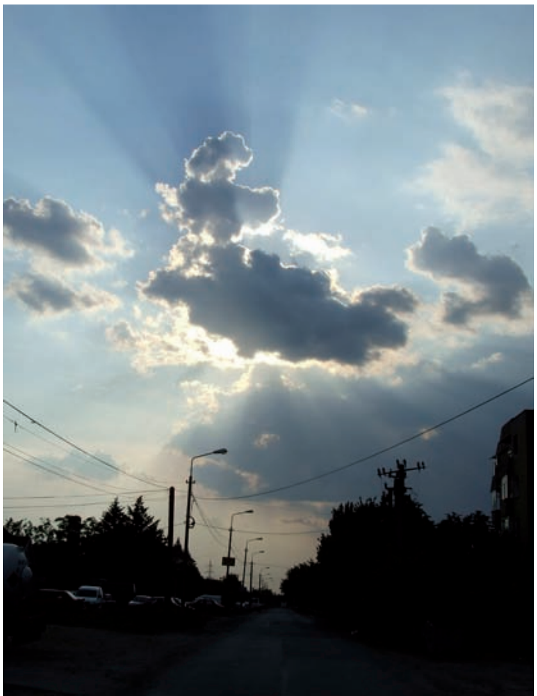
This document is structured as follows. Chapter 2 sketches our vision of a sustainable energy system in 2050. The reasons for choosing this particular approach are discussed in Chapter 3. Chapter 4 deals with what is necessary in order to realise this vision. The lessons that can learned from the vision are presented in Chapter 5. The document is concluded with a chapter on sustainability criteria for nuclear energy, CO_2 storage and biomass.

2. Vision of a sustainable energy system in 2050

2.1 Outline

It is now 2050. The global production of oil peaked in 2015 and has dropped steadily since then. This has led to large fluctuations and great increases in the price of oil, which is now about $100 a barrel. The price of natural gas has also increased considerably. A reduction of CO_2 emissions to 60% below 1990 levels has been achieved as a result of the European Union's ambitious climate policy. It took many years to reach this goal, starting with a 20% reduction in 2020. The challenge now is to maintain the momentum of emission reductions. We must continue to increase the share of renewable energy sources and to reduce energy demand and the growth in such.

There has been a large reduction in the contribution of fossil fuels, such as oil and gas, which has resulted in a corresponding decrease in our dependence on their import. As a result of climate policy, coal with CO_2 capture is being applied on a large scale for the production of both electricity and hydrogen. The hydrogen is used in the transport sector. Large quantities of coal are imported, and there are strict guidelines regarding labour conditions and environmental issues in the countries of origin.



Sustainable energy sources are growing rapidly and are now responsible for more than 35% of all energy production. Biomass, wind energy and solar energy play major roles. Much has been achieved in energy conservation: the average annual rate of energy savings has been 1.5%, partly thanks to intensive energy saving strategies, with great attention paid to entirely new technologies and concepts.

The energy needs of homes and other buildings have been greatly reduced: they are now mainly met with solar energy, electricity and natural gas. Biomass is primarily used as fuel for freight transport, shipping and aviation, as there are not many substitutes for oil products in these sectors. A small proportion of biomass is used for electricity production by means of advanced gasification processes. The European agriculture and forestry sectors have begun to produce large amounts of biomass in a sustainable way. In addition, biomass and biofuels are imported only if the sustainability of production and conversion has been proven. Nuclear power is used on a limited scale, as only about 50% of European countries support nuclear energy. Although new nuclear reactors have been built in these countries, the net contribution of nuclear energy has barely grown. CO_2 capture & storage is utilised on a large scale for electricity generation and in industry. In total, as much CO_2 is now captured as is emitted. There is sufficient storage space for this, for example in aquifers and depleted gas fields.

The large-scale use of sustainable energy sources required improvements to the electricity grid: because solar and wind-based electricity generation is weather-dependent, the grid needed to be able to mitigate the consequent fluctuations in the amount of electricity generated by the numerous small solar panels and large wind turbines. Intelligent grids and interactive grid management were developed to fulfil this need. Grids have been strengthened and extra electricity storage facilities provided.

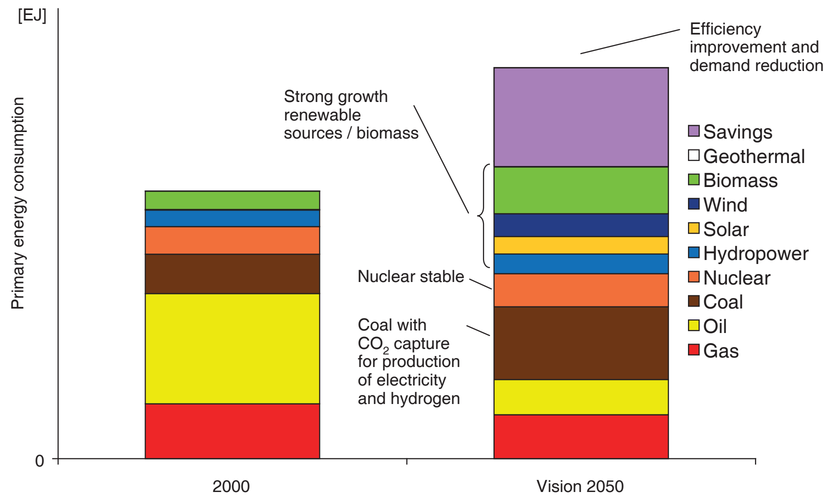


Figure 1 Primary energy consumption in Europe in 2000 and, according to the sustainable vision, in 2050

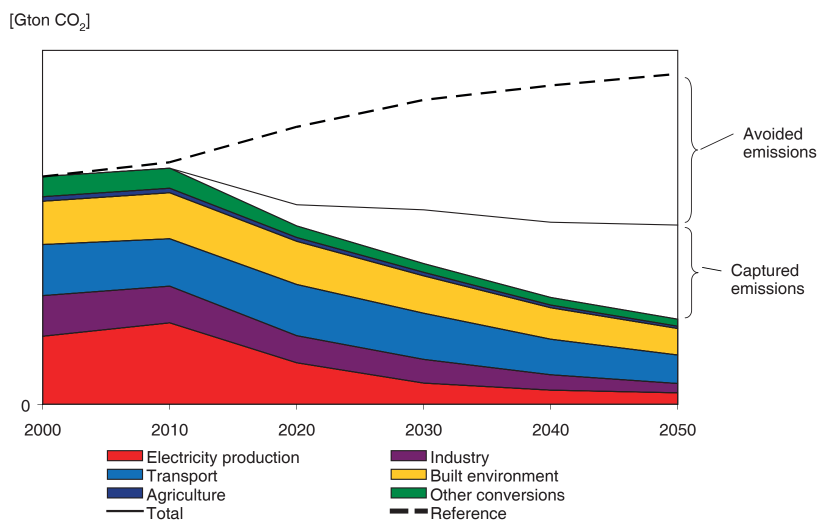


Figure 2 CO_2 emissions and capture per sector in Europe

It took a great deal of effort across the board to achieve the 60% reduction in CO_2 emissions. The greatest reduction has been in electricity production, as CO_2 emissions can be directly captured at the power stations and many renewable sources are used. Later on in this chapter we discuss the measures taken in the various sectors in order to realise this emission reduction.

2.2 Built environment

In the built environment (private houses, business premises, and public and government buildings), the high gas prices combined with strict regulations and continuous public information campaigns have contributed to a significant reduction in the demand for heating, especially in the northern EU countries. There has been a continuing shift from gas to electricity as the principal source of energy in homes and other buildings. New housing estates are not provided with a gas network, although gas is still important for older neighbourhoods. Climate change has led to a drop in the demand for heating but a rise in that for cooling, especially in southern Europe.

Almost half of the buildings in Europe have been built since 2000 and therefore comply with stringent insulation standards. The buildings have been designed such that their orientation to the sun allows maximum use to be made of passive solar energy. Regulations require older buildings to be re-insulated during their renovation. Large-scale heat storage is used at both the home and the neighbourhood level. Electric heat pumps serve the remaining demand for heating and cooling. Older buildings and neighbourhoods make use of gas-fired heat pumps. Green gas (synthetic natural gas; SNG) is rarely used, as almost all of the available biomass is reserved for the transport sector.

Figure 3 House using solar energy

There is active use of solar energy at home: photovoltaic cells (with or without heat production) produce electricity, hot water and electric cooling. There is a strong emphasis on conserving energy, partly by means of intelligent energy management and efficient appliances that have to comply with strict EU standards.

The consumption of natural gas has decreased, and no hydrogen infrastructure has been put in place for housing; as a result, there has been no great increase in the combined generation of electricity and heating based on natural gas or hydrogen (micro-CHP). Moreover, electricity production is now so efficient that the benefit of a combined heat & power system in one's attic has been nullified. The importance of comfort in homes and other buildings has been a major consideration in the application of new technology. Initially, such technology was received with scepticism by builders and engineers, but their resistance has been overcome by making energy efficiency a central issue in the construction business: numerous demonstration projects are carried out before new methods are applied on a large scale, the experiences of builders and engineers are meticulously recorded and attention is paid to energy conservation during their training.

2.3 Transport sector

The transport sector has changed considerably. The transition towards alternative fuels and drive trains was hastened by the scarcity of oil products and a strict climate policy. Because road charging have made driving more expensive, more use is now made of public transport, which has become flexible and of good quality.

Passenger cars are now much more efficient, thanks to efficient internal combustion engines and the use of hybrid concepts and lightweight materials. A significant improvement in the storage capacity of batteries has not been achieved, however, limiting the utilisation of the plug-in hybrid with a detachable battery that is charged from the mains. Traffic jams are now rare, as a result of the implementation of advanced ICT. Motorists are advised in good time about delays, and automatic distance sensors on motorways have led to a great reduction in the number of accidents. Many people now telework and thus avoid the rush hour and save fuel. In cities, a large number of deliveries are made by vans powered by electric motors that run on batteries or fuel cells, and this has improved local air conditions.

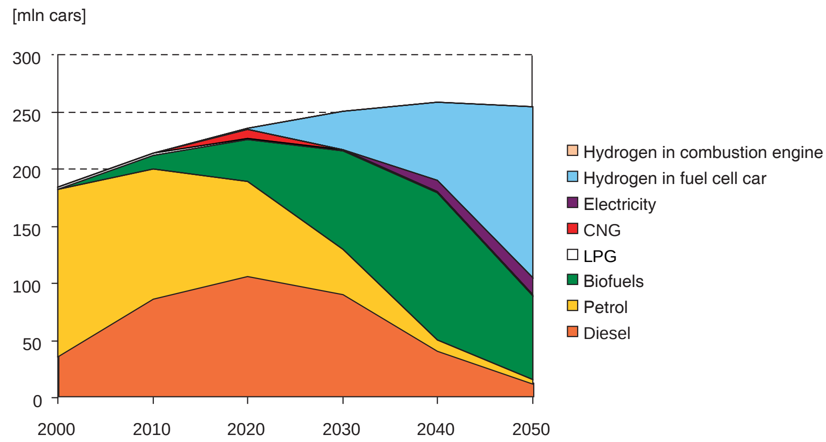


Figure 4 Passenger cars and fuel types in Europe

Hydrogen is available at the pump in many areas of Europe. Initially, hydrogen was largely produced from natural gas with CO_2 capture, but, due to the high gas prices, coal with CO_2 capture is now preferred. Because of the sharp drop in the price of fuel cells, there is rapid growth in the number of cars powered by such cells. This is partly a result of the European campaign in 2020 for '100,000 fuel cell cars', which encouraged manufacturers to produce large series of these vehicles. Due to the high efficiency of the fuel cell, cars powered by such cells are as cost-efficient as cars that have a petrol or diesel engine. Approximately 50% of all passenger cars are now hydrogen-fuelled; others still use biofuels, either pure or mixed with oil products. Bicycles, many of which have an auxiliary electric motor, are used for travelling short distances, facilitated by the many safe cycle paths that have been created across Europe.

Freight transport that involves long distances and heavy loads is still reliant on diesel. Most carriers opt for bio-diesel, which is made from woody plants using such advanced processes as the Fischer Tropsch process. This also applies to buses, which are standardly fitted with a bio-diesel hybrid, except in a number of cities where hydrogen-fuelled buses are used. Shipping has also turned to bio-diesel. Only about 30% of the diesel used in Europe is made from mineral oil. Aviation is largely dependent on bio-kerosene.

2.4 Industry

The European industrial sector has undergone fundamental changes. Although the chemical sector continued to use oil for longer than other sectors did, it finally switched to biomass as a raw material for chemicals and transport fuels. Biorefinery has allowed the many materials present in biomass to be fully exploited. Syngas technology (gasification at high temperatures) is the prevailing method for producing synthetic fuels. The raw materials, which include biomass and coal with CO_2 capture, are first converted to syngas, from which Fischer Tropsch diesel and hydrogen can be produced, as can synthetic materials, ethanol, etc. As a result of the intensive climate policy, demand has arisen for new products, such as synthetic materials for the production of lighter weight cars.

Although production has increased in the industrial sector, the consistent deployment of the various techniques to save energy has led to a 25% reduction on year 2000 levels. The application of the 3R principle (reduce, reuse, recycle) throughout the lifecycle of materials has been a significant factor in this reduction. Additionally, there is a clear trend towards the use of electricity (which is produced in a climate-friendly manner) in preference to oil, gas and coal.

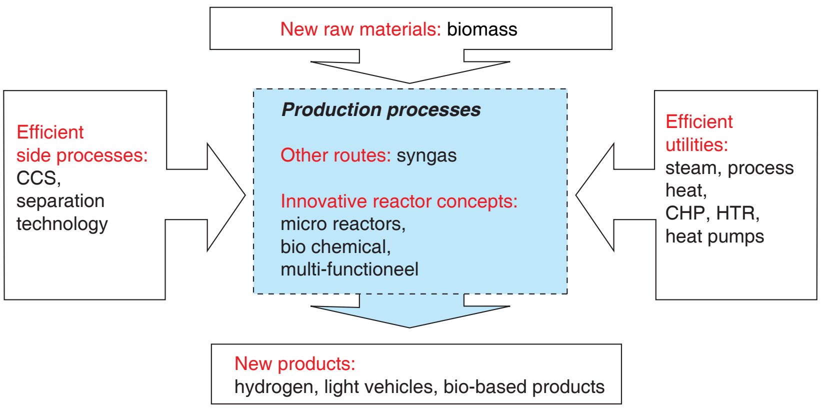


Figure 5 The principal areas of attention for energy conservation and CO_2 emission reduction in industry

To this end, innovative processes have been developed that yield considerable energy savings. A good example is the use of biochemical reactors, which employ enzymes and bacteria to make products from biomass. Multifunctional reactors – in which the processing and the separation of raw materials are combined – are also commonly used. Many industrial processes now take place in microreactors, in which reaction conditions are more easily controlled, leading to energy savings. Many processes are now more selective; for example, some use new catalytic converters that consume fewer raw materials and produce much less waste. Great effort has been put into R&D in order to develop these new technologies. CO_2 capture technology is used not only for the production of electricity, but also in various industrial processes (e.g. for the production of steel, cement, hydrogen and ammonia). In these cases, the CO_2 flow is relatively concentrated, which renders CO_2 capture cheaper than it is in the electricity sector.

Much attention has been paid to energy conservation in such ancillary processes as wastewater treatment and in the production of such utilities as heating, electricity and hydrogen. Heat pumps are used to supplement heating systems and to utilise excess heat for cooling systems. Heat storage and cogeneration are used wherever possible. In some countries, small-scale, inherently safe nuclear reactors (high-temperature reactors; HTRs) are utilised for combined heat & power systems. The remaining demand for heat is largely satisfied by low-grade biomass. Separation technology has become more efficient, and much energy has been saved by replacing distillation processes with membrane or absorption processes.

2.5 Electricity generation and distribution

About 40% of all electricity is still generated using fossil fuels (principally coal with CO_2 capture). Renewable energy sources account for approximately the same amount, while about 20% is generated using nuclear power. Electricity production costs have risen by a factor of 2.5 since 2000.

The exploitation of renewable energy sources has been the principle method used to achieve this drastic reduction in CO_2. Wind energy, photovoltaic solar energy (PV) and solar thermal systems for electricity generation (concentrated solar power; CSP) supply most of the electricity. Wind power capacity has risen by a factor of 15 since 2000. About 100 GW of offshore capacity has been installed in the form of 200 wind farms each delivering 500 MW; most of these farms are in the territorial waters of the Netherlands, the United Kingdom, Denmark and Germany. Bathers on Mediterranean beaches have also become accustomed to the sight of wind turbines on the horizon. The wind capacity on land has grown to about 140 GW. Land wind turbines generally have a capacity of 3 MW, which is slightly lower than those at sea (5 MW). Wind farms are widespread throughout Europe, especially in the windier countries.

CSP plants are most prevalent in southern Europe and are equipped with large heat buffers. Solar PV systems have become much cheaper. After 20 years of extensive subsidy programmes, consistent R&D support and intensive cooperation between the industry and scientific institutes, the cost price of solar energy could compete with the price of electricity to small-scale consumers. About three quarters of the electricity from solar energy is produced using PV.

Biomass is used flexibly in large 'X to Y' gasification plants, which can switch both between fuels and between end products (e.g. heating, electricity, transport fuels). The contribution of biomass to electricity production is somewhat limited (5%), as most of the available biomass is needed as feedstock for transport fuel.

Following on the EU-wide decision concerning a solution for the safe disposal of nuclear waste, there is sufficient support for nuclear energy in about half of the Member States to allow for the construction of new, fourth-generation nuclear power plants that meet the highest safety standards. In addition, a large number of third-generation European pressurised reactor (EPR) plants are still in use. An important landmark was the establishment in 2015 of a supranational body to supervise the worldwide use of fissionable materials in order to support non-proliferation.

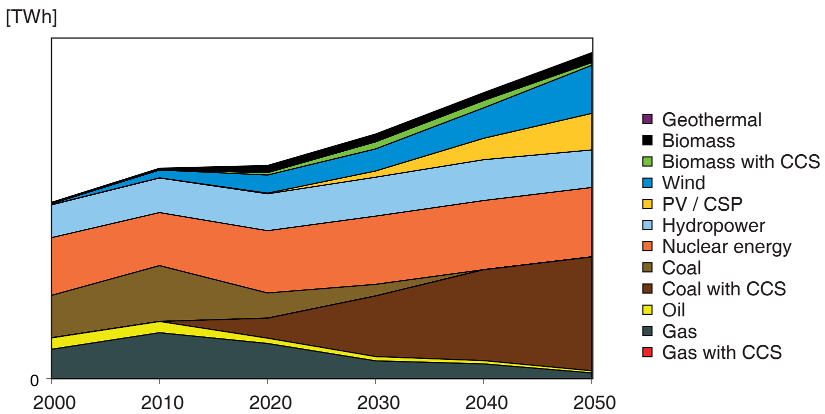


Figure 6 Electricity production in Europe

Both the transmission and the distribution of electricity now employ advanced ICT in order to match the location and the timing of supply and demand. Since about 25% of the supply has become dependent on intermittent sources, such as wind, sun and small-scale hydroelectric power, it is imperative to match the timing of supply and demand of electricity efficiently. In a country such as Denmark, even 50% of the electricity supply is dependent on intermittent sources.
Large-scale power plants (i.e. nuclear power stations and coal-fired plants with CO_2 capture) are not very flexible and thus are ill-suited to regulating supply. This is why small-scale capabilities play an important role. Electric heat pumps, for example, can be switched on and off according to demand as they use heat buffers to assist in the provision of heat. Electricity storage by means of electrochemical storage techniques has recently been introduced. Another method of synchronising supply and demand is through market mechanisms that encourage end users to react to the spot price of electricity (real-time pricing). Another important element is the compensation of electricity shortages and surpluses throughout the European electricity grid. These different opportunities are in competition with each other, in both the short term (operational) and the long term (investment). There is a need for further flexibility due to the growing role of intermittent energy sources. To this end, a number of countries have started to build large reservoirs that are pumped full when there is a surplus of electricity, and that drive water turbines when there is a deficit. Many institutions and regulations in this field have been changed to allow for these developments.

Alongside the large-scale production of electricity (from coal, nuclear energy, offshore wind and CSP), a share of the electricity is produced decentrally, for direct use by customers or to be fed to the grid locally. This occurs at the medium voltage level in the case of cogeneration (or combined heat & power generation; CHP), wind on land and small-scale hydroelectric power, and at the low voltage level in the case of solar PV and micro-CHP.

Here, cogeneration is dependent on the availability of local fuels or such energy sources as biomass, hydrogen or green gas (SNG). Where the availability of local sustainable energy sources allows for many small-scale sources of electricity, the electricity grids are controlled using advanced ICT technology so that supply and demand can be adequately matched at any given moment.

3. Why this specific vision of a sustainable energy system?

3.1 Clean energy is a basic need in 2050

Energy is one of the basic necessities of modern humankind. In the first place, energy has to be available. In 2007, large parts of the world population had no or only limited access to energy. Once there is availability, supply must be reliable. It must also be affordable, and be produced in a clean manner. Although 'clean' primarily entails that it is produced without causing harmful emissions, the concept is much wider. We will discuss this in the next paragraph.

A pyramid of energy demands can be constructed that is analogous to Maslow's hierarchy of needs. This hierarchy asserts, in short, that clean and sustainable forms of energy generation will be used only if they do not damage the availability, security and affordability of the energy supply.

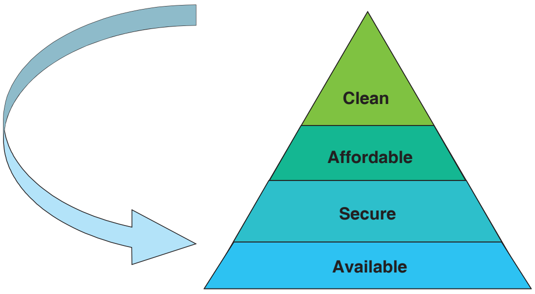


Figure 7 Energy needs pyramid, after Frei, 2005

‘Clean’ has now, in 2050, become an important part of the energy pyramid. We know that the pollution resulting from energy generation and consumption is a threat to other basic human necessities.
The climate change that has resulted from the increased concentration of CO_2 in the atmosphere jeopardises food supply and thus, indirectly, the security of humankind. Equally, soot and NO_x emissions are health risks and are a particular menace to city dwellers. This is why we prioritised the search for clean energy sources in Europe and why ‘clean’ is one of the benchmarks for any energy option. Thus, all new energy generation should be clean, and these new, cleaner options should also be secure and affordable.

The vision presented in this document meets these criteria. In Europe in 2050, there has been a 60% drop in CO_2 emissions since 1990; all sectors show a decrease of at least 30% on 1990 levels. Figures in the field of electricity production are even higher because this field offers the most opportunities, including CO_2 capture & storage.

The vision for energy is equally realistic in the areas of security and affordability. Now, in 2050, the oil and gas reserves have diminished further and prices have risen accordingly, to 100 $\$_{2005}$ a barrel for oil and to 75 $\$_{2005}$ a barrel of oil equivalent for gas. The price of coal is rising, but not as sharply. The price of CO_2 has remained stable for two decades at approximately 100 €/tCO_2. Other resources have largely taken over the roles of oil and gas. Europe has become less dependent on imported energy resources. The demand for a secure supply of energy is met by diversifying energy generation across various technologies. Of the many technologies that can be applied for the generation or consumption of energy, the most affordable are now making the greatest contribution.

This energy vision draws a plausible and accurate picture. For example, both at the time of writing and in 2050 there are limits to the availability of mineral oil, natural gas and biomass, and this has been taken into account. The applied integral analysis revealed that there are conflicting claims between sectors that need to be resolved. For example, biomass can be utilised for electricity generation, for producing chemicals or for transport. To make these choices, the authors took into account such considerations as the availability of alternatives for biomass, the contribution to the reduction of CO_2 emissions and affordability.

Alongside the reduction of CO_2 emissions, many other factors determined the changes that have come about in energy systems by 2050. An important example is the improvement of air quality by lowering soot and NO_x emissions caused by traffic and industry. In 2050, the problem of health-endangering air pollution is a thing of the past. The general public now accepts such options as nuclear power and biomass, but only if stringent conditions have been met.

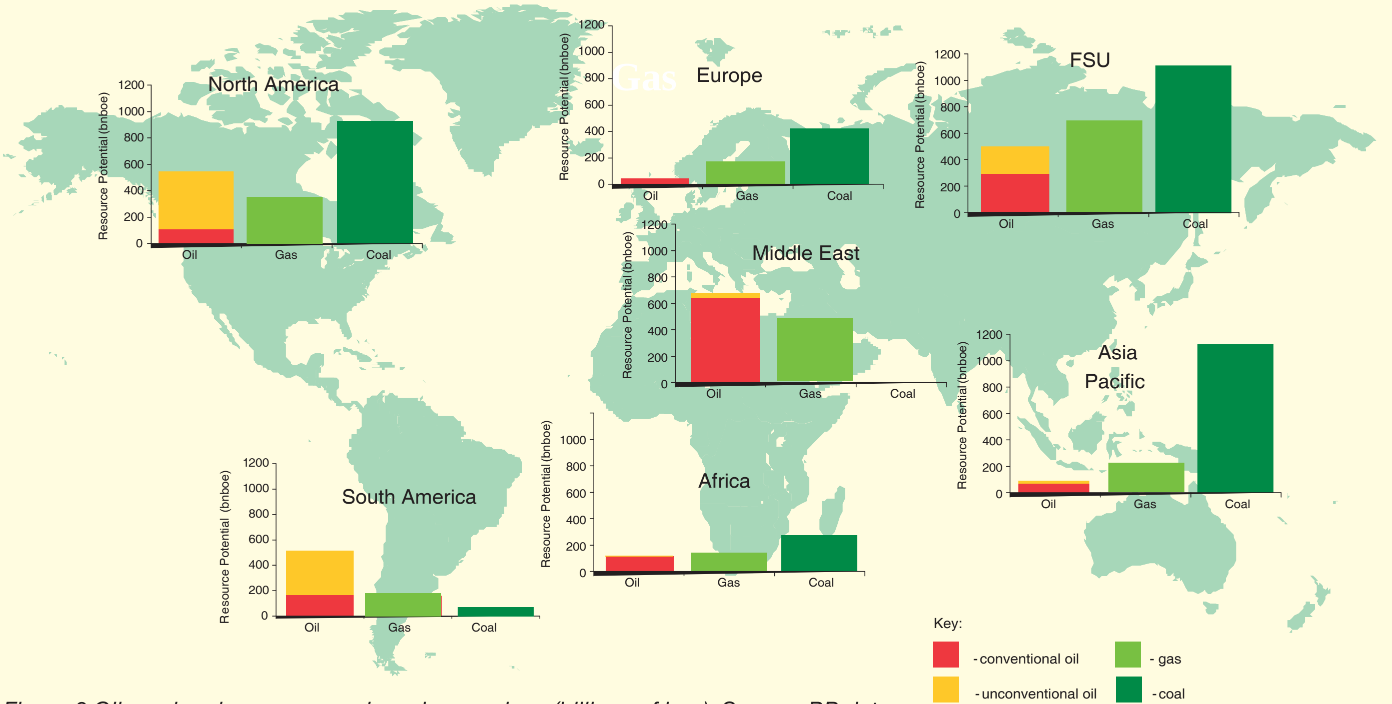


Figure 8 Oil, coal and gas reserves in various regions (billions of boe). Source: BP data

Security of supply

Oil, gas, coal and uranium are all finite resources. At present these four energy carriers serve 90% of European energy requirements. At some point they will run out, but the answer to the question when this will happen varies per resource and is dependent on who you ask. Many believe that the supplies of oil and gas will be depleted by the end of this century, with spectacular price rises as a result. It is not expected that there will be a lack of supplies of coal and uranium by 2050. However, the increased demand for coal will certainly lead to a rise in prices, and some studies suggest that there may even be a problem of supply (Kavalov, 2007).

To guarantee security of supply, there obviously must be reserves available, but the energy carriers also have to be physically supplied. Supply from the Middle East, North Africa and the former Soviet Union is not always assured, in many cases for political reasons. Figure 8 shows that it is these regions that have the greatest reserves of oil and gas. Coal reserves are more evenly distributed around the globe. Uranium is mostly mined in Canada and Australia. Unconventional oils (tar sand and oil shale) are to be found in large quantities in several parts of the world; however, the extraction process produces extremely high CO_2 emissions. Europe itself has very limited supplies of oil and gas. To improve security of supply, Europe will have to turn to the sun, the wind, biomass and coal.

Security of supply is a matter not only of reserves, but also of the security and reliability of trading routes and means of transport. Diversification in these aspects should therefore be another priority.

Current energy consumption in Europe and the world

The growing demand for energy is perhaps the most important reason to develop a more sustainable energy system, especially when this growing demand is met with the use of oil and coal, which results in increased CO_2 emissions. In 2007, 50% of CO_2 is emitted by the rich industrialised nations, in which only 18% of the world population lives. The remaining 82% of the world population is responsible for the other 50% of global CO_2 emissions.

The EU is at present a major consumer of energy, and is responsible for a large proportion of global CO_2 emissions. Although there are countries that emit more CO_2 per capita, there are many more countries whose energy consumption is far lower than that of Europe, as can be seen in Figure 9. The energy consumption-related CO_2 emission per capita in China and India is currently only 10-30% of that of a European. The historical trend in Europe is for energy consumption to grow in step with the growth in the economy. The explosive growth of the Chinese economy and the expected growth in India, Latin America and Africa will lead to a higher consumption of energy per capita. In 2050, the energy consumption of many people around the world will be similar to that of the average European. Europe's proportion of global energy consumption will be a great deal smaller than it is today. Competition for the available resources will be much fiercer, and as a result it will be more difficult to reduce CO_2 emissions. This makes the choice for sustainable sources in Europe a necessity.

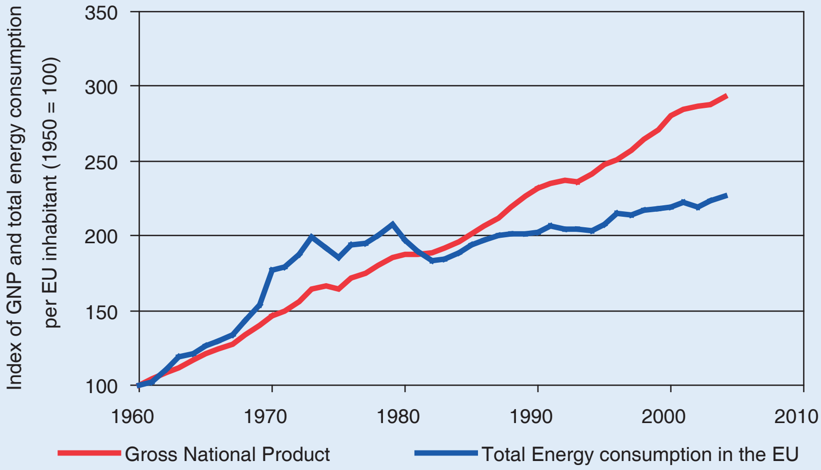


Figure 9 GNP and energy consumption per capita in the EU-15. Source: IEA, 2006

Prosperity has grown in the Europe of 2050, while the consumption of energy per capita has not risen accordingly. Population growth in Europe began to slow down after 2010, and has been dropping ever since 2020.

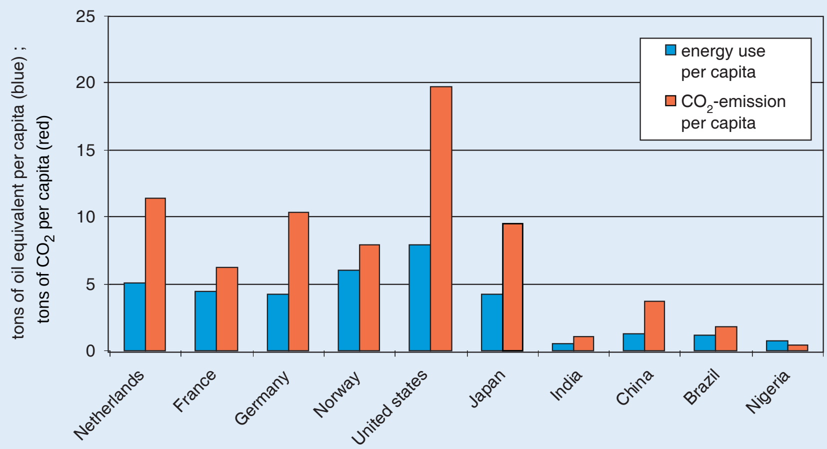


Figure 10 Energy consumption and CO_2 emission per capita in a number of countries in 2004. Source: IEA, 2006

In the Netherlands, there is a relatively high rate of CO_2 emission per capita, partly because of the high concentration of industry in the country. The inhabitants of France produce relatively little CO_2, thanks to the large contribution of nuclear energy to the production of electricity.

Climate Change

The UN Intergovernmental Panel on Climate Change (IPCC) published its fourth climate report in 2007. It confirms that global warming is taking place (IPCC, 2007). Snow and ice are melting on a massive scale and the global sea level is rising. It is highly probable that this warming is caused by human activities, especially the emission of greenhouse gases and new forms of land exploitation. The concentration of CO_2 (the most significant greenhouse gas) in the atmosphere increased from 280 ppm (parts per million) in the year 1750 to 379 ppm in the year 2005.

Due to the inertia of the climate system, the temperature could continue to increase for decades, even if the concentration of CO_2 in the atmosphere were to remain constant. However, this concentration will not remain constant: over the last 10 years, it has increased each year by an average of 1.9 ppm. Depending on the rise in CO_2 concentration and on the reaction of the climate, the global temperature is expected to increase by between 1.1 and 6.4°C. Table 1 illustrates the effects of various levels of temperature increase. Even the most optimistic scenario requires drastic measures to combat the effects of the increase in temperature. Climate change also affects energy production, including for instance hydroelectric power stations and the production of biomass.

A maximum rise of 2°C is seen as the level at which the dangerous effects of climate system changes are likely to remain limited. To restrict the temperature rise to 2°C, the greenhouse gas concentration in the atmosphere must not be allowed to exceed approximately 450 ppm. To achieve this goal, global greenhouse gas emissions must start to drop by 2015. In 2050, global emissions should have dropped by 50-80%. Thus, the average 2% annual increase in CO_2 emissions must be swiftly turned into a decrease.

Table 1 Global effects of temperature increases. Source: PCCC, 2007

Temperature increase compared to 1990				
Effect on:	1-2°C	2-3°C	3-4°C	4-5°C
Water 	Hundreds of millions of people exposed to increased water-related problems			App. 20% of the world population exposed to flooding
Ecosystems 	Increased extinction of amphibians Increased coral reef bleaching	20-30% of all species in danger of extinction	Extensive dying of coral reefs	Extinction of species
Food 	Crop yield decreases at lower latitudes and increases at higher latitudes		Adaptive capacity of many crops is exceeded at lower latitudes	
Coastal areas 	Increased damage due to flooding and storms	Millions of people additionally under risk of flooding	30% loss of coastline and wetlands	

3.2 Criteria for sustainability

In 2050, energy supply is considerably more sustainable. The term 'sustainable development' was defined by the Brundtland Commission in 1987 as:

… development that meets the needs of the present without compromising the ability of future generations to meet their needs.

This definition may be interpreted in many ways, but there is a consensus that there are three defining factors: the economy, the environment and social conditions. In turn, each of these factors includes aspects that determine the sustainability of each form of energy technology. The list presented in this chapter shows a large number of these sustainability aspects. The term sustainable energy is often simply used to describe renewable resources, e.g. such resources as the sun, wind and biomass, that do not impinge on finite reserves. The list shows that sustainable energy is a much more far-reaching concept.

Table 2 Aspects of sustainable energy

	Aspects
Economy	
Energy efficiency	Positive effect on primary use
Reserves	Availability of primary source
	Finiteness of primary source
	Influence of price of raw materials on energy price
	Demand for other supplies (e.g. storage capacity, silicon)
Security	Location of supplies, import-dependency
	Diversity of sources
Affordability	Cost in comparison with other technologies
	Effect on international competitiveness
	Opportunities for cost reduction
Reliability	Always available or intermittent?
	Limits due to grid capacity
Economic activity	Relationship with other economic activities
	Effect on employment
	Opportunities for developing innovative activities
Environment	
Climate change	Direct CO_2 emissions
	CO_2 balance along the entire chain
	Emissions of non-CO_2 greenhouse gases
Air quality	Emissions of NO_x, SO_x, particles, etc.
	Location of emissions (for instance in inner cities)
Biodiversity	Land use in vulnerable areas
	Direct effect on flora and fauna
	Emissions into the ground
	Soil exhaustion
Landscape change	Interventions to landscape
Water quality	Emissions into water
	Use of water ('fossil' water)
Long-term effects	CO_2 storage, nuclear waste
Social	
Poverty	Influence of raw material extraction on prosperity in country of origin
	Influence on local availability of food
Labour conditions	At mining of raw materials
	While using an energy technology
Equality	Contribution to wide availability of technology
	Availability of technology for future generations
Safety	Safety of generation
	Safety of raw material extraction
	Safety of waste transport and storage
	Abuse by malignant parties
Freedom of choice	Imposed measures and loss of freedom of choice

For example, should the production of biomass prove to be damaging to rainforests or food supplies in developing countries, it cannot be deemed sustainable.

It is clear that most major energy technologies do not meet all of the criteria for sustainability. The use of fossil fuels depletes reserves, nuclear energy and CO_2 capture will burden future generations with

Table 3 The principal criteria for sustainability
Effect on primary energy consumption – Is more, or less energy used?
Finiteness of the primary source – Might there be a supply problem?
CO_2 balance along the entire chain – Are large or small amounts of greenhouse gas emitted?
Land use in vulnerable areas and influence on local availability of food
Safety of waste transport and storage

storages of waste, wind farms leave their mark on the landscape and large-scale energy savings will lead to a reduction of choice for individual citizens. However, not all aspects carry equal weight. Table 3 lists the most important criteria that are used to determine whether or not a certain technology or source of energy is expedient in terms of sustainable development.

The goal is to achieve an entirely sustainable energy system. However, this will not be achieved by 2050. Wind energy, solar energy and energy conservation largely fulfil the most important criteria. Other options, such as using oil products for transport and coal without CO_2 capture, are clearly not sustainable. The other main options – biofuels, nuclear energy and electricity derived from coal with CO_2 capture – do not meet all of the above criteria. Chapter 6 discusses the conditions by which they may be rendered acceptable from a sustainability viewpoint.

4. How can we arrive at a sustainable energy system?

To the basic question of whether a sustainable energy system can be created, the short answer is: "Yes – but it will require a complete change in the way energy-related decisions are made, not only on the part of governments, but also consumers. And it will require consistent, decisive long-term policy, successful development of the necessary technology and, last but not least, action in other parts of the world." For example, it is vital that the US, China, Brazil and India cut their emissions of greenhouse gases. The process will also have to continue beyond 2050, because a truly sustainable energy supply will not be achieved within a few decades.

For many years now, economic growth has gone hand in hand with increased consumption of energy and fossil fuels. In the necessary change of direction, cutting greenhouse gas emissions will have to be a consideration in many more decisions. Our contribution to that shift is known as ROBUST, from the Dutch acronym for "realisation of a coordinated strategy to reduce greenhouse gas emissions" – although it also embraces targets related to security of supply.

The main components of the ROBUST approach are as follows.

A. The establishment of long-term objectives for greenhouse gas emissions and security of supply, coupled with their operationalisation in the medium term. These objectives must be approved and supported by all stakeholders, and they also need to be harmonised with other areas of policy: agriculture, the internal market, the environment and foreign relations.
B. The formulation of a clear vision on the portfolio of technologies needed to achieve the objectives set, as well as the establishment of an RD&D roadmap to bring about the necessary innovation, and provision of the tools and resources required for that process.
C. The development of a consistent set of policy instruments to help technologies through their development phases, although without distorting the market, including incentives to phase out less efficient technologies.
D. The establishment of limits and standards: strict ceilings for greenhouse gas emissions and clear standards for energy consumption and the use of sustainable energy – all tightened up on a regular basis.
E. Cooperation and communication between governments, businesses and the public with respect to RD&D, the market introduction of new technologies, the construction of new infrastructure. This should overcome resistance and lead to a stable investment climate.
F. Regular monitoring, evaluation and reflection, in order to review the results achieved and adjust the ROBUST approach accordingly.
G. The international dimension: involving other parts of the world.

Concrete objectives can be formulated for those particular elements of the ultimate sustainable vision which are certainly needed. This is especially the case during the market introduction phase. It is essential, though, that this be done timely. For a new technology to be made mature and competitive, it is vital that experience is built up. One example of such an objective is the European programme to put 100,000 hydrogen-powered vehicles on the road by 2020. That is the number required to build a sufficient basis for practical experience and so make the product improvements needed to conquer even more of the market. International technology agreements can be an effective tool to this end, too; under them, each signatory country commits itself to production or implementation volumes for a particular technology.

One precondition for the transition to a more sustainable energy system is a balanced set of policy measures. Each phase of a technology's evolution towards marketability demands a different type of policy instrument. In the early stages, R&D policy is needed to develop an innovative technology. After that, the government encourages demonstration projects in a variety of markets so that experience can be gained in actually using the new technology – a process known as "niche accumulation". The next stage is to subsidise the technology. Eventually, however, as more is learned and economies of scale come into play, such financial support should become redundant. But this is also the time to deal with those users lagging behind and still using inefficient systems. One way of doing that is to impose stricter standards as time goes on.

Governments have to provide the commercial sector with a clear picture of the long-term prospects for new technologies. One approach is to formulate objectives, another is to put in place a policy covering a period of sufficient length. This contributes towards a stable regime, although external factors – the deregulation of the electricity market is one example – are also important. It is crucial that the private sector be able to operate within a clear and stable policy framework, and one which sends out the right price signals, for example, a high and reasonably stable market price for CO_2.

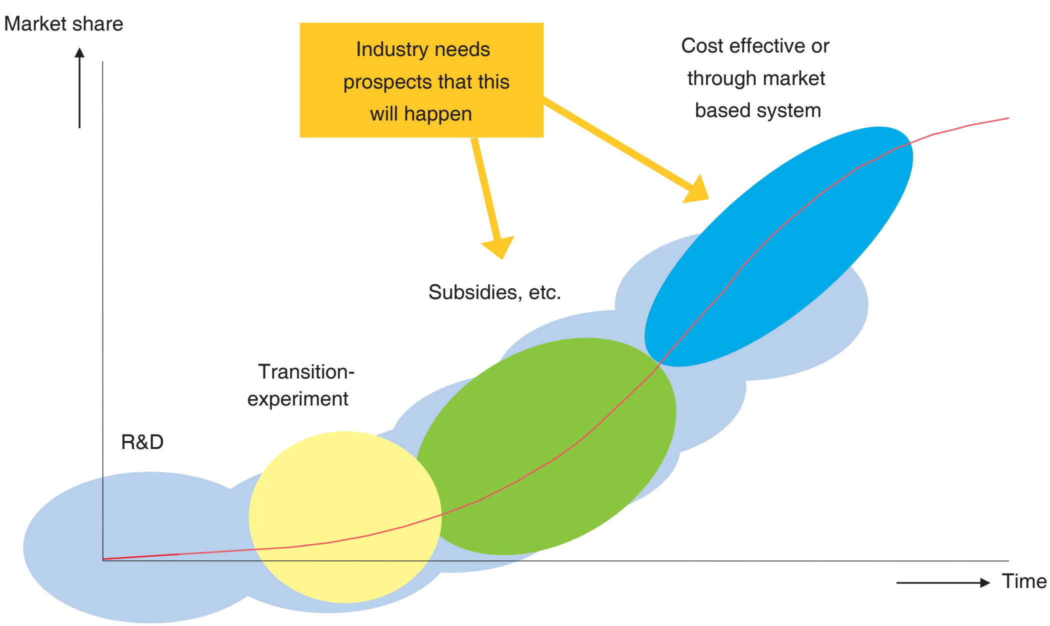


Figure 11: Use of policy instruments in the ROBUST approach

The necessary changes will only come about if all concerned are made aware of the urgency involved and are prepared to work together in new ways. The process of transition in the Netherlands is designed to achieve that, but far more integration is still required for it to have real impact. Work is also needed to bring about greater harmonisation of climate, energy, foreign and R&D policy. And that, in turn, will affect other government objectives – in mobility, agriculture, innovation, industrial policy and so on. All of these effects need to be mapped out so that properly considered choices are made, resulting in a clear and stable situation where investment in new technology is encouraged. If any sector encounters problems in applying new sustainable technologies, it should be able to approach the government to discuss possible solutions.

The government also has an important role to play in setting up new energy infrastructures, such as those for CO_2 capture and hydrogen. There is no need for the government to invest directly in these itself, but what it must do is ensure that the right conditions are created for development of those infrastructures by market players.

Decisiveness is essential to effective policy. All too often, key decisions take years to make. The time constants in the supply of energy are long, so any delays in modifying the system can have immense repercussions. It is therefore vital to be resolute in sticking to robust choices and not to change course midstream although, of course, there must be room for new ideas.

It is important, too, that new initiatives be examined in respect of their impact upon climate policy. It is possible, for example, to produce transport fuels from coal – but this would double CO_2 emissions throughout the entire chain compared with the production of petrol and diesel from crude oil. CO_2 generated during fuel production can be captured, but CO_2 emitted from vehicle exhausts cannot. The government needs to be alert to developments of this kind, and to intervene promptly when such initiatives are put forward.

Governments need to monitor continuously in order to know which policies are effective and which are not. Based on that kind of evaluation, policy can be updated and improved.

5. Strategy implications

5.1 Things could turn out differently

What if Europe fails to achieve its 2020 targets for the reduction of CO_2 emissions, and even more cuts thereafter? Depending on price developments and the availability of fossil fuels, various scenarios are possible. One of these is outlined below, although many more are of course conceivable.

"High oil and gas prices, security of supply under threat, no climate policy"

In this scenario, oil and natural gas reserves decline more rapidly. As a result, coal gains importance but it is unable to cover the entire shortfall in oil and gas supplies, so overall consumption of fossil fuels declines. Coal's share of power generation rises, though. Moreover, coal is used by industry on a large scale to manufacture transport fuels. Since the price of fossil energy sources is high, there is a strong incentive to save energy and to convert to sustainable sources – particularly short-term solutions like wind and biomass – and nuclear power. The annual rate of energy saving is a little less than 1%. Nuclear and wind energy are encouraged, thus gaining a larger share of the market. Biomass is used to produce transport fuels, and also as a supplementary fuel in electricity generation.

The so-called X-to-Y power station, without CO_2 capture, also does very well under this scenario. There are few changes to the energy infrastructure, although more facilities are built for the processing of coal and biomass. Most of these are situated close to seaports. CO_2 emissions in 2050 are 10% higher than they were in 2000. This has a significant impact upon the climate, resulting in major social instability.

This scenario clearly portrays a less sustainable energy system. Given the fundamental uncertainty of those factors which shape the future, countless other similar scenarios could be devised. Experience teaches us that the factors in question are difficult to control, meaning that the future could be either more positive or more negative than we envisage. Whether a good climate policy is ever put in place, for example, depends very much upon how geo-political relationships unfold, how willing countries are to reach workable compromises, if disasters attributable to climate change prompt concerted action and so on. All these matters are very difficult, if not impossible, to influence. Yet some relevant factors can be controlled by means of technology and behaviour. If more sustainable sources of energy become widely available at an affordable price, that will make the vision outlined in the previous chapters more likely. Developing the necessary technology can thus be regarded as a "shaping strategy": one which increases the chances of a particular outcome. Another option is to make technologies that limit the impact of negative developments more widely available and affordable. They do not so much reduce the likelihood that the negative factors will occur as make it easier to offset their effects. This is known as a "hedging strategy".

On the technology front, too, things may not develop as foreseen in the previous chapters. The cost of producing solar and wind energy might decrease faster than foreseen, for example. Or perhaps it will be possible to import more sustainable biomass. In that case, it will become possible to scale down the contribution made by coal with CCS much faster. Or it will be easier to reduce the use of nuclear energy. Another possibility is that the operational life and storage capacity of batteries improve so much that electrical power becomes the new standard in the transport sector, rather than fuel cells.

As innovation continues, there will doubtlessly be surprises. Not every future development can be foreseen at the time of writing. Maybe artificial photosynthesis, or so-called "blue power" (electricity generated by the controlled mixing of fresh and salt water) or nuclear fusion will come to play their part in the supply of energy. Or even some as-yet totally unforeseen invention. However, it is highly improbable that any currently undiscovered technology will come to make a sizable contribution before 2050.

For these reasons, a wide portfolio of technologies for research and development must always be chosen. And this should be balanced in its other aspects, as well – for instance, incorporating technologies with both short-term and long-term potential.

5.2 Implications for technological research

Figure 12 compares a number of important technologies on their potential contributions to reducing CO_2 emissions, as set out in the vision presented in Chapter 2, and to improving security of supply. Saving energy is the option which scores best in both respects; it has the greatest potential to reduce reliance upon imports as well as to cut emissions. Research in this field covers a very broad spectrum of activities: reducing demand by changing behaviour; increasing efficiency in a wide range of sectors; limiting energy losses through better insulation; replacing old plants with new, more efficient ones; integrating systems; and recycling and reuse.

Solar and wind energy are both expected to enjoy huge growth between now and 2050, by which time they will be making a major contribution to the supply of energy. They are dependent upon imports only in so far as the raw materials for the equipment are concerned, although the availability of the crystalline silicon remains an important risk factor in the development of photovoltaic technology. Moreover, the consumption of solar energy could also entail its import – from large-scale PV or CSP generating facilities in North Africa, for instance. Both solar and wind energy have the disadvantage that they are not constantly available, and hence require more research into power storage technologies. Wind energy's potential in Europe is fairly well known; the limiting factor is lack of space for the generating capacity. Solar energy has a huge potential, but how fast it will grow is going to depend very much on how the costs evolve. For this reason, both technological developments and incentive policies are focusing on reducing the cost price.

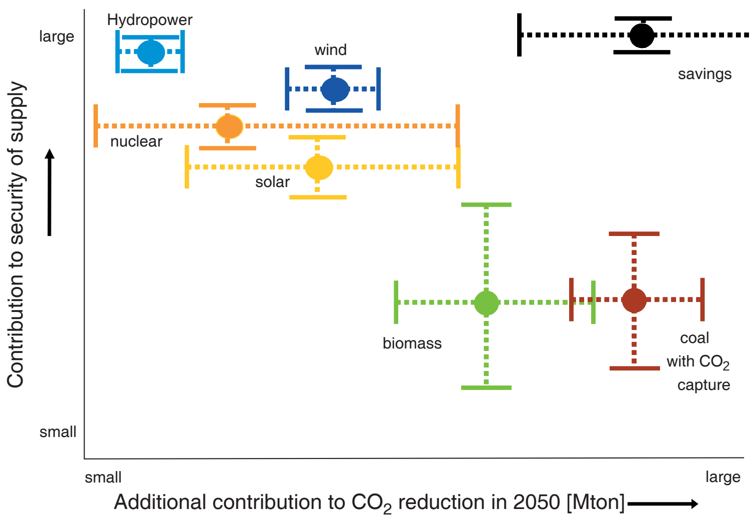


Figure 12: Additional contribution to the reduction of CO_2 emissions in 2050, compared with 2007 – the vision presented in chapter 2 – versus contribution to security of supply for various energy sources and technologies.
The bars indicate the margins of error in either variable.

Two other sources of energy with great potential are coal with CCS and biomass. There remain major uncertainties about their actual prospects, however; these are related to the public acceptance of CO_2 storage and to the availability of biomass. Both sources are widely available in Europe, but imports on a large scale will also be needed. Biomass can be used in many sectors, but its transport and industry applications are most obvious because there are few alternatives available there. In this respect, the development of technology for the so-called second-generation biofuels (produced from lingo-cellulose rather than food crops) is crucial, as is safeguarding reliable and sustainable biomass production. The technology for the generation of electricity from coal with CCS is not yet commercially viable, so developments are currently focusing upon reducing its cost. Also crucial to this technology is ensuring the reliability of sufficient storage capacity for the CO_2.

Nuclear energy's contribution to reducing CO_2 emissions is limited because the future scenarios do not envisage the construction of many new nuclear power stations; activity will be confined mainly to the replacement of existing capacity. The nuclear contribution could increase if public acceptance of this technology in large parts of Europe were to grow. Meanwhile, its potential contribution to security of supply is high because the quantities of uranium required are relatively small and they are obtained from stable nations like Canada and Australia. The technology has been on the market for decades, whilst development in such areas as building intrinsically safe generating plants and reducing the production of nuclear waste are very much ongoing.

Progress towards making new technologies available involves passing through a number of phases (see also Figure 11).

- Technical feasibility.
  In the case of several potentially important future options, either the raw materials or the technologies needed are not commercially available. For some, the technology is still in or has only just emerged from the experimental phase. Large-scale CO_2 capture, for example, is not yet a mature technology. And although first-

Things could turn out differently...

The Hague, February 2041.

Owing to the changed currents caused by the many wind farms in the North S large sections of Ducht coastline ha been washed away and a number o islands have been created between England and Denmark. The Nether has laid claim to these islands and p construct an airport on one of ther compensate for Schiphol Airport w now threatened by flooding.

Dubai, February 2030.

Oil price reaches historic low.

Corrected for inflation, the price of oil is now under the 1960 level. Analysts point to the breakthrough of the electric car as the major factor. OPEC is to abolish itself.

Sjanghai, 1 September 2023.

From today, the 30 million inhabitants of the Chinese city of Sjanghai will only be allowed to power their vehicles with fuel cells. The local government has invested in a comprehensive network of hydrogen filling stations and is subsidising the purchase of fuel-cell-powered cars, buses and scooters. In this way, they hope to quickly overcome the problems of air ...y. The local fuel cell ... be stimulated. It is ...ing this mass market ...rp drop in the price of ...r term.

Saudi Arabia joins the association of wind-power producing countries

Algiers, August 2015.

Because CSP created shade in the desert, moisture is extracted from the air and transported to the soil. This local climate change has created vegetation and the CSP fields must be regularly mown and clipped. The extra biomass that this creates increases the CSP yield. The number of jobs in the Sahara region has increased sharply.

Middelburg, 2030. The Netherlands' exporting position strengthened by uranium from Zeeland. After celebrating 40 years of safe nuclear energy in 2026, the market for uranium extracted from clay in Zeeland was grown further. This is a windfall for a province that is plagued by flooding.

...uston, November 2025.

Following the terrorist attack with a long steel cable and the obsolete freighter Otapan-II, construction work on new offshore windmills has come to a halt. It appears to be ...ible to protect an offshore

Groningen, 3 March 2049. East Groningen has been ravaged by earthquakes caused by a rise in land level. The earthquakes, which were 2.4 on the Richter scale in Stedum last night, where linked to the large-scale storage of CO_2 in the empty Groningen gas fields. There were already earthquakes in Groningen at the end of the twentieth century and the beginning of the twenty-first century caused by a drop in land level through natural gas extraction.

OSMOSIS PLANT NEAR THE DEAD SEA CELEBRATES 30 YEARS IN OPERATION

Offshore coal-mining off the coast of Mexico halted by hurricane season

Monte Carlo, 21 May 2044.

Fast-charging batteries decide the Monaco Grand Prix

The Ferrari of Harald Schumacher has won the sixth grand prix of the season thanks to the team's new fast-charging unit. The batteries supplying power to the electric motors in the wheels of ...e Ferrari were fully charged in an unprecedented 27 seconds.

Scheveningen, 27 May 2049.

The coral reef off the coast of Scheveningen has been included in the list of protected ecosystems according to the HABITAT directive. Since the warming of the seas water and the erection of a larg... number of wind farms, an extraordina... ecosystem has been created here. Th... are excursions every third Tuesday o... month: please assemble at the "K... information centre, just behind the...

Amsterdam, June 2033.

Solar billionaire from Niger buys Ajax

Ozman Dkourajtu - the owner of several large solar-power plants in Niger - has bought Ajax football club from the Arabian oil sheik Mohammed Al Hazab. Dkourajtu acquired his wealth through the sale of solar power to Europe. This is the fourth European football club to be bought by a billionaire from Niger, which was one of the poorest countries in the world only a few decades ago.

generation biofuels satisfy a need, the great breakthrough will only come with the second generation: synthetic biofuels, which are going to require a lot more R&D before they reach the market.

- Cost reductions through R&D and market experience.
  Some technologies are available now, but are still too expensive. Solar energy and hydrogen-powered vehicles are good examples of this. For these technologies even to reach the market, an incentives policy is essential; any real breakthrough requires a sharp reduction in actual costs. What is particularly needed is research into manufacturing processes, cutting down on the use of expensive raw materials and so on. This could involve the improvement of existing technology, but also developing new ones from scratch; an example of the latter is organic PV panels. Cost reductions are also achieved by building up experience and exploiting economies of scale. But a market needs to be created for the new technology, too. Every innovation must pass through the phase prior to large-scale – and hence affordable – production, so starting early has its advantages. It is important as well, though, that a technology be allowed sufficient time to deal with what has been learned so that it can be incorporated into the next generation in a way that reduces costs. For that, a finely tuned combination of market incentives and R&D policy is essential. Also important for cutting costs are the price of raw materials and making sure that new technologies are not over-dependent upon scarce materials.
- Removing obstacles.
  Even technology which is already on the market requires further development. Nuclear energy, for example, has been in commercial use for decades and yet is still encountering obstacles to its expansion: the waste problem and concerns about reactor safety. Current R&D activities are therefore concentrating upon creating inherently safe reactors and upon ones which produce much less highly radioactive waste – the so-called Generation IV reactors. There are also obstacles in the way of CO_2 storage, such as uncertainty concerning capacity and the safety of the storage sites. These can be dispelled with the help of geological research.
- Increasing potential.
  Many sources of energy which are dependent upon imports of fuels like oil, coal and biomass are the subject of research into increasing production. Particularly in the case of biomass, there remain huge doubts regarding the fuel’s potential and so a great deal of further investigation is still required. Another example is research into possible alternatives to current fuels, such as platinum in fuel cells or copper in wind turbines.

5.3 Costs and benefits

Given the extent of the climate problem, it is going to be necessary to introduce a broad portfolio of technologies. There is no one magic formula which will make our energy system sustainable; the solution will have to come from a varied combination of technologies. That will spread the risk if some fail to live up to current expectations. It is also worth looking at the costs of specific technologies; the price of the vision described in Chapter 2 will be several hundred euros more per capita in 2050 than a non-sustainable alternative scenario. This is not money which is being withdrawn from the economy, but rather represents a shift in cash flows. Moreover, it is offset by benefits such as a reduced risk of major social disruption caused by climate change and less dependence upon oil and gas imports, as well as new jobs in a variety of sectors, such as building, agriculture and the manufacture of clean energy technologies.

Figure 13 shows an estimate of the additional cost of excluding specific technologies, compared with the picture painted in Chapter 2. This can only be indicative, of course, since the future cost evolution of any technology is shrouded in uncertainties. Moreover, these estimates are dependent not only upon the actual cost of the technologies concerned but also upon the extent of their contribution to the energy system in 2050.

We looked first at the consequences if CO_2 capture and storage (CCS) were to be unavailable – perhaps as a result of problems finding storage locations. This would increase costs considerably, by some €150 billion, because about half of CO_2 emissions could be captured in 2050. If CCS were not available, those emissions would have to be prevented in some other way – specifically, by saving more energy and by making more use of renewable energy.

It is also possible that public opinion in Europe might develop in such a way that it is decided to phase out nuclear power and not to build any more nuclear plants. In that case, given the high price of gas, a large number of new coal-fired power stations with CO_2 capture would have to be built. Solar and wind energy would also make a larger contribution. The additional costs of this vision amount to some € 70 billion in 2050, raising the price of electricity by 25%.

Finally, if less biomass can be imported, costs rise accordingly. Were Europe to have to produce 20% more biomass itself, for example, then the total cost would increase by € 17 billion. Meanwhile, the hypothetical costs of excluding new wind farms are somewhat higher: about € 30 billion.

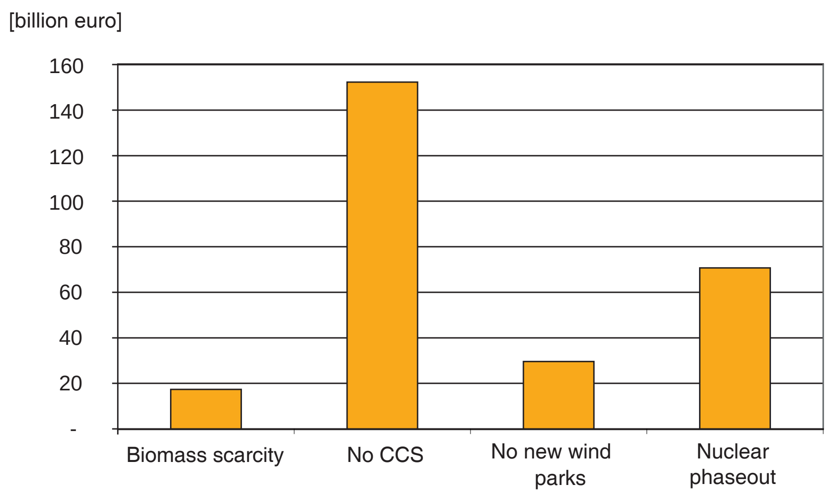


Figure 13: Additional costs in 2050 of excluding specific technologies in Europe, as compared with the sustainable vision described in Chapter 2

6. Sustainability criteria for nuclear energy, CO_2 storage and biomass

Earlier in this document, we described what we mean by sustainability. But there are some technologies which remain the subject of debate as to their true sustainable credentials. In this chapter, therefore, we formulate preconditions for the inclusion of nuclear power, CO_2 capture and storage (CCS) and biomass in a sustainable energy system.

6.1 Nuclear energy

6.1.1 Background

Of all the electricity production technologies, nuclear energy is currently making the greatest contribution to the European supply: some 30%. Around the world, more than 400 nuclear power plants are supplying power grids.
This number is growing, although that is now mainly due to the construction of stations outside Europe. To consider this technology's future contribution from the perspective of a sustainable energy supply in Europe, below we discuss the sustainability aspects of nuclear energy. The key factors in this respect are uranium reserves, radioactive waste, plant safety and the risk of proliferation.

6.1.2 Reserves

Uranium reserves must be used as efficiently as possible

Current uranium consumption is about 67,000 tonnes a year. Known reserves available at a price of less than US$ 130/kg are approximate 4.7 million tonnes, enough to last seventy years at the current rate of use (Redbook, 2006). These reserves are spread throughout the world, with the main concentrations being in Australia, Canada and Kazakhstan.

Between 1985 and 2005, the low price of uranium meant that there was hardly any new exploration. Were the price[1] to double, the commercially viable reserves would increase many times over. And there are also unconventional reserves, such as the uranium present in seawater (4000 million tonnes).

[1] A price increase of $50 per kg of uranium would imply a cost increase of a few tenths of €ct/kWh

Research programmes into fourth-generation reactors are seeking to make the use of uranium up to 100 times more efficient. And thorium – which is at least as common as uranium in the crust of the Earth – can also be used to produce nuclear fuel. In principle, then, the actual availability of fuel is not an issue in the debate surrounding the sustainability of nuclear energy.

The recovery of raw materials must be as safe and environmentally friendly as possible
The environmental impact of uranium recovery and processing depends upon the method of extraction used, how the process is managed and what happens to the "tailings" – the residue left after ore processing. Depending upon how deep the ore is, it can either be mined underground or extracted from open-cast pits on the surface. After recovery, the ore is broken or ground up and then treated with acid to separate the uranium itself. Alternatively, so-called "in situ leaching" can be used, whereby the ore is dissolved at the recovery site and then pumped to the surface as a liquid.

Tailings are radioactive. But by properly sealing the reservoirs in which they are dumped, it is possible to reduce their environmental impact to a level equivalent to the emissions from naturally occurring radon.
Sustainable uranium extraction must be as environmentally friendly as possible and restoration of the landscape after mining ends is one important precondition for sustainability. With this in mind, in situ leaching is the preferred recovery method. To ensure that all forms of extraction safeguard the environment, they should comply with internationally accepted standards.

6.1.3 Waste
Around 2015, a political decision must be taken concerning the permanent storage of high-level radioactive waste. If new nuclear plants are to be built, waste disposal must be arranged before construction starts
From the sustainability point of view, waste management must be so good that the impact upon people and the environment is kept to a minimum at all times. The challenge in disposing of nuclear waste is to keep that part of the material which will remain radioactive for the longest period separate from the biosphere.
Currently, the only financially and technically feasible solution is long-term storage deep underground. Europe has still not succeeded in completing any permanent disposal facility for high-level radioactive waste[2]. In the Netherlands, it has been decided to reprocess spent nuclear fuel elements with the result that approximately 95% of the material can be recycled. The remainder is stored by COVRA, the Central Organisation for Radioactive Waste, awaiting a permanent disposal solution. Another option used elsewhere in Europe is the so-called "direct cycle", where spent fuel is stored temporarily at or close to the nuclear plant itself so that it can be transferred to a permanent underground storage facility as soon as that becomes available. Countries to have adopted this approach include Sweden and Finland. In the future, advanced techniques such as partitioning and transmutation may become possible. These can reduce the radioactive life of high-level waste to a few hundred years. However, more research is required before such solutions can be used on a wide scale.

Political decisions need to be taken, preferably at the European level, concerning the final disposal of radioactive waste.

[2] These are being built in Finland and Sweden.

6.1.4 Safety

Until 2030, the safety of new nuclear power stations must be guaranteed using barriers, redundancy, passive systems and long response times

Nuclear reactors are systems containing a large quantity of radioactive material. Their safety is assured through natural processes and the so-called "defence in depth" concept: a series of successive barriers and redundant systems designed to prevent the spread of that material in the event of an incident. Thanks to these measures and to the physical security casing around the reactor itself, the risks of accidents and of radiation escaping into the environment are very small. At new plants, moreover, it is possible to cool the reactor by natural circulation so that the cooling system remains operational even in the event of a major incident. There is also a system underneath the reactor to capture escaping material in the event of a core meltdown. Meanwhile, other systems help to extend response times[3]. All in all, these measures have reduced the potential impact of human error to a minimum.

From 2030, new nuclear power stations must meet an additional criterion: no evacuation outside the gate

The development of the fourth generation of nuclear reactors has been set in motion with a view to making them commercially available by 2030. As well as excellent safety and reliability, these are subject to new security criteria: a very low risk of core damage and no need for evacuation off the plant site in the event of an emergency.

Artist's impression of the European pressurised reactor (EPR) in Finland.

[3] Period after an accident in which no human intervention is yet required.

6.1.5 Proliferation

Proliferation is the uncontrolled spread of nuclear technology and material for military use. At the moment, there are particular proliferation problems with North Korea – which has already developed a nuclear weapon – and Iran, which is suspected of attempting to do so.

Nuclear reactors and the nuclear fuel cycle are designed in such a way that the risk of proliferation through them is kept to a minimum. Nevertheless, there is still a risk. This, however, is not linked to European decisions on whether or not to build new nuclear plants – and all the more so because there is currently a global surplus of plutonium and highly enriched uranium. For this reason, the role of international institutions and treaties is crucial.

International monitoring of fissile material from nuclear power plants and other sources must be strengthened.

The civil use of nuclear energy entails a risk of proliferation. Although power stations themselves make no direct contribution to that phenomenon, other systems within the fuel cycle – such as enrichment plants and reprocessing facilities – do have the potential to do so. In theory, fissile material can be used by states with corrupt regimes for both civilian and military purposes. It is for this reason that enrichment and reprocessing plants are subject to monitoring by the International Atomic Energy Agency (IAEA) under the Non-Proliferation Treaty. The scope of that convention is limited, however, because countries like Pakistan and Israel have not signed it. If the plants and the fissile material at them were to become the legal property of a supranational entity – the IAEA in an enhanced form, for example – the Non-Proliferation Treaty would be much more effective. This is something the IAEA itself has been calling for; it is up to the international political community to act.

Concern about terrorism has increased since 11 September 2001. It would be practically impossible for a terrorist organisation to develop a nuclear bomb, due simply to the size and complexity of the systems required. However, the use of a so-called "dirty bomb" is a real threat. This is a device which spreads radioactive material in a conventional explosion.

That material would be difficult to obtain from the nuclear fuel cycle, though, compared with other relatively easy sources such as the medical sector.

6.1.6 Fourth-generation nuclear reactors

The Generation IV Forum was founded to encourage the development of nuclear energy which complies with the sustainability criteria described above. Its eleven member countries have drawn up a road map for six promising reactor concepts. The objective is that commercial systems be on the market by 2030, having completed the concept development and demonstration phases.

Two of the fourth-generation concepts are open fuel cycle reactors, which should be able to produce both hydrogen and electricity efficiently; these are the very high temperature reactor and the supercritical water reactor. Another four concepts – the sodium-cooled, lead-cooled, gas-cooled are molten salt-cooled reactors – use a closed fuel cycle; they are designed to make the best possible use of nuclear fuel and to recycle radioactive waste. Not all of these concepts will comply with each sustainability criterion to the same extent.

6.2 Coal with CO_2 capture and storage

6.2.1 Background

In the vision outlined earlier in this report, CO_2 capture and storage (CCS) makes an important contribution to reducing greenhouse gas emissions: by 2050, as much CO_2 is being captured in Europe as is emitted. Given the fuel's cost and reserves, coal-burning seems the most likely activity to which CCS will be coupled. But the technology could also be applied to, say, biomass. In a certain sense, CCS is a typical hedging technology; if coal does have to be used, then this method at least ensures that its drawbacks in terms of CO_2 emissions are reduced. Strictly speaking, CCS with fossil fuels is not sustainable because the energy system is still drawing upon finite reserves and future generations will be saddled with huge volumes of stored CO_2. Moreover, application of this technique reduces the efficiency of coal-based generation and so, by extension, the security of energy supply. CCS should thus be regarded as a transitional technology on the road to a truly sustainable energy system. After a period of growth, it will be widely used for

a few decades and then scaled back. In 2050, however, it will still be in its growth phase.

Below we describe how coal with CCS can be applied in a manner we consider acceptable.

6.2.2 Sustainable coal consumption

Imported coal must be obtained from safe mines

The EU imports large quantities of coal from countries like Russia, Kazakhstan and Australia. Not all provide safe working conditions, whilst open-cast mining sometimes scars the landscape. The coal used in Europe should come from mines which put safety first and keep their environmental impact to a minimum. We should also look critically at human rights, working conditions and wider effects for the environment.

Conversion should be as efficient as possible

The world has large reserves of coal, but they are not inexhaustible. So the fuel's conversion into electricity must be made as efficient as possible. The use of current CO_2 capture technology actually reduces a coal-fired power station's efficiency by more than 10 percentage points. To substantially reduce the so-called efficiency penalty by 2050, new technology needs to be developed. This can then be applied at power stations with much higher efficiencies than those currently in operation. Ultimately, the efficiency of a coal-fired power plant with CO_2 capture needs to exceed 45%.

6.2.3 Sustainable, safe CO_2 transport and storage

Storage sites are safe and annual leakage does not exceed 0.01%

The most promising prospective locations for CO_2 storage are depleted oil and gas fields and so-called saline aquifers, underground layers of porous rock holding salt water. Particularly in this latter category, there is huge potential capacity in Europe. The risks involved in storage are gradual leakage of the CO_2 and its rapid build-up in populated areas.

Gradual leakage of CO_2 from reservoirs would make CO_2 storage less efficient. The maximum permissible rate of leakage should be set at 0.01% a year. According to a recent Special Report published by the Intergovernmental Panel on Climate Change (IPCC), there are probably enough reservoirs capable of meeting this strict requirement. The aquifers must comply with all kinds of conditions before they are deemed suitable for CO_2 storage, with comprehensive geological screening an absolute must. One of the risks is that CO_2 will slowly and unnoticed leak from an underground storage site into a lake. This must be prevented. Ongoing monitoring of CO_2 reservoirs will also be essential.

The rapid release of a cloud of CO_2 would present an immediate danger to humans and animals. In calm weather, such a cloud could hang in the air and cause suffocation. Such a sudden release from an underground reservoir consisting of porous rock is impossible, but that is not the case with empty gas fields. They should in theory be sealed because they held natural gas for millions of years, but leaks could occur through the same route used to extract that gas: the boreholes. However, there is technology available which is capable of detecting leaks and preventing the escape of large volumes of gas; much experience in this field has been gained from the transportation of flammable natural gas, hydrogen and similar substances.

CO_2 must be transported with a minimum of risk

Captured CO_2 will be transferred to the storage site by pipelines, which will inevitably pass through populated areas. Here again, the sudden release of a large cloud of gas is a real risk, but one which can be countered by the use of good detection equipment.

6.3 Biomass

6.3.1 Background

Biomass is a source of energy with a lot of potential. It is flexible both in its applications and in the variety of raw materials from which it is derived. On the other hand, there are still questions on how sustainable it really is, particularly when considering the entire chain from cultivation to final use. There also remain great uncertainties about how much biomass will actually become available for energy generation in the future. And Europe will probably have to import it from other parts of the world – as, indeed, it is already doing now.

6.3.2 Sustainable biomass production

Biomass cultivation must not harm biodiversity

The cultivation of biomass has the potential to damage biodiversity if, for example, tropical rainforests are destroyed to make way for large-scale plantations. This can also adversely affect the animal populations, including protected species, in those areas. That is a particular concern in developing countries. To prevent this, information about changes in land use is required. In this respect, there is a difference between direct and indirect changes which makes monitoring difficult. The choice of reference year is also relevant. From a sustainability point of view, the best option is to cultivate biomass only on land which was previously barren or used for other crops.

Biomass cultivation must not damage the environment.

As with other agricultural crops, the cultivation of biomass for energy production can involve the use of artificial fertilisers or chemical pesticides, which may damage the environment. Moreover, excessive use of fertilisers can upset the greenhouse gas balance of the biomass produced (see below).

Other risks include soil depletion or dehydration. Ligneous crops consume more groundwater because their root systems are deeper. In some situations, there is also a potential for erosion. In conventional agriculture, there exist international "good practice" guidelines which generally can also be applied to biomass cultivation.

Bio-energy must never be generated to the detriment of plentiful, affordable supplies of food or basic materials

The flexibility of biomass as a raw material for foodstuffs, materials and fuel alike gives it many advantages. One drawback, however, is that any crop is likely to be sold for the use which generates the greatest income. And that has the potential to distort markets and to increase the inequalities between Western and developing nations.

The rapidly growing demand for fuel biomass is already leading to shortages of food crops and the concomitant price increases.

In Mexico, a doubling in the price of tortillas in 2006 was partly attributable to a sharp increase in demand for maize from the US bio-ethanol industry and for cattle feed from Asia.

Since the second-generation of biofuels based upon lignocellulosic crops will compete much less directly with food production and generate a higher energy yield per hectare, it is recommended that the transition to them be completed as soon as possible.

Many organic residues, such as waste and manure, also count as biomass. But their use throws up different dilemmas. Although it is of course better to recycle such products than to dump them, that also removes one of the incentives to generate less waste in the first place. Moreover, this activity could again distort markets if residues are diverted into energy generation instead of being put to more valuable uses – for example, the production of chipboard.

Biomass cultivation must not have a detrimental effect upon human prosperity and well-being in the country of origin

The cultivation of biomass should have a positive effect upon the local economy. And, more generally, it should improve well-being in terms of working conditions, human rights, property and usage rights and social conditions, as well as government integrity by, say, countering corruption.

Production conditions

In practice, it is difficult to effectuate these sustainability criteria. What we should be striving for is the international certification of biomass for all uses, not just energy. It may also be preferable to use biomass grown in Europe where possible, since its cultivation in developing countries entails greater sustainability risks and is more difficult to monitor. And with global demand expected to increase, resulting in upward pressure on prices, Europe should not become over-dependent upon biomass production in other parts of the world.

6.3.3 Chain sustainability: the greenhouse gas balance

In the long-term, biomass-based energy applications should generate at least 70% less greenhouse gas emissions than the reference fossil fuels

In theory, bio-energy can be made carbon neutral. In other words, the amount of CO_2 produced during its incineration or gasification has already been offset by the crop's absorption whilst growing. There may, however, be additional emissions in the chain from cultivation, through harvesting and shipping, to conversion.

There are large differences between chains, and also within them. Particular attention needs to be paid to the use of artificial fertilisers during cultivation, since they can release considerable amounts of the greenhouse gas nitrous oxide (N_2O). Also important is whether or not agricultural waste can be recycled. Biomass incineration produces particulates, sulphur oxides (SO_X) and nitrogen oxides (NO_X), but during gasification, acidifying and polluting substances can be eliminated before they are released. Depending upon the purity of the biomass, though, contaminated residues may be left over.

6.3.4 Potential: is there enough biomass?

Estimates of the potential from bio-energy vary widely. This is because they are based upon different factors, all of which are uncertain.

- Economic and population growth, human diet – particularly the proportion of meat – and their impact upon the demand for food.
- The intensity of agriculture.
- Developments in land use: will hitherto uncultivated areas be exploited, and to what extent will biomass be grown for non-energy applications?

Table 4 provides a general estimate of the global potential for biomass, with the ranges based upon IPCC scenarios incorporating different assumptions about population growth, diet and rate of technological development.

In quantifying the vision for energy presented in this report, we have made use of a study into the potential technical feasibility, without increasing environmental impact, of bio-energy in the EU-25 (EEA, 2006). That is estimated at 12 EJ per annum, 35% of which is obtained from residue flows. Compared with the potentials given in Table 4, this is a conservative figure.

6.3.5 Sustainability of biomass use

On the consumption side, priorities need to be set for the use of biomass. It has its greatest CO_2 impact when used to generate electricity. On the other hand, there are several alternative ways in which emissions can be reduced in electricity generation, whereas the the options are more limited in the transport sector.

But transport biofuels make a direct contribution to cutting oil dependence. This applies particularly to second generation biofuels, because they have a better CO_2 performance and make fewer demands upon agricultural land. In the long term, the transport sector could switch to bio-hydrogen for use in fuel cell vehicles. Thanks to the high efficiency of those cells, this is the solution which will deliver the best yield in terms of kilometres driven per hectare of crop. For freight transport, however, the effect will probably be less noticeable as bio-diesel is likely to remain predominant. The Fischer Tropsch process for the production of that fuel has the great advantage in that its first stage, gasification of biomass, can also be applied in the manufacture of hydrogen.

Table 4 Realistic biomass potentials in 2050

	Biomass cultivation for energy[a] [EJ_{prim}/yr]	Biomass residue flows[b] [EJ_{prim}/yr]
World	147-447	53-73

[a] Source: Hoogwijk, 2004, assuming that the realistic potential is that part of the technically feasible potential with production costs of less than US$4 per GJ.
[b] Source: Smeets et al, 2004.

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List of abbreviations

boe	Barrel of oil equivalent
CCS	CO_2 capture and storage
CO_2	Carbon dioxide
CHP	Combined heat and power
CSP	Concentrated solar power
EPR	European pressurised reactor
HTR	High-temperature reactor
IAEA	International Atomic Energy Agency
ICT	Information and communications technology
IPCC	Intergovernmental Panel on Climate Change
NOx	Collective abbreviation for various nitrogen oxides
PV	Photovoltaic
RD&D	Research, development and demonstration
ROBUST	Realiseren van een overkoepelende broeikasgas uitstootreductie strategie ("realisation of an overall strategy to reduce greenhouse gas emissions")
SNG	Synthetic natural gas

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ANNEX Assumptions used in quantification of the energy vision

The basis used in developing the sustainable vision is the MARKAL energy model. The database used was developed as part of the EU project CASCADE MINTS Part 1 and covers the energy system in Western Europe (EU-15 plus Norway, Switzerland and Iceland).

Prices and availability of fossil fuels

The fuel prices below have been used. These are taken from the POLES model and are based upon a scenario in which increasing CO_2 taxes are levied, rising from € 10 per tonne in 2000 to € 85 per tonne in 2050.

Table 5 Energy prices in the sustainable vision

$\$_{2005}$/barrel	2000	2030	2050
Oil	27	61	97
Gas (Europe)	19	49	73
Coal (Europe)	10	18	23

It is assumed that an "oil peak" will occur in Europe in about 2015, after which consumption starts to decline. The lower threshold for oil consumption is derived from the IEA World Energy Outlook 2006. It is also assumed that only about half of the 2020 volume can be recovered in 2070. Between 2030 and 2070, the data is interpolated.

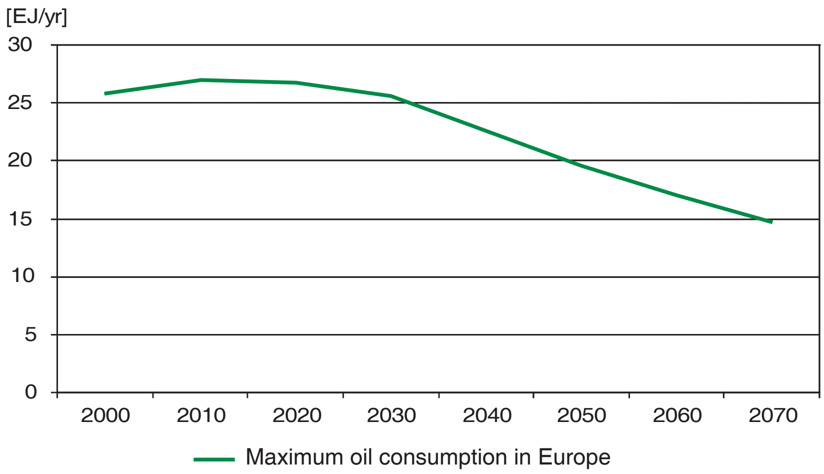

Figure 14 Modelling the oil peak in Europe

Climate policy

The objective of climate policy is to reduce CO_2 emissions with 60% between 1990 and 2050. Each sector must cut its emissions by at least 30%, with the model determining where the remaining reductions are achieved at minimum cost.

Biomass

In quantifying the vision presented in this report, we have made use of a study into the potential technical feasibility, without increasing environmental impact, of bio-energy in the EU-25 (EEA, 2006).

That potential is estimated at 12 EJ per annum, 35% of which is obtained from residue flows. In principle, biomass imports have been modelled in such a way that they may not exceed the volume for ten new EU member states.

Nuclear energy
The future development of nuclear energy is uncertain because public acceptance is an important factor. In this report, we have assumed that each European nation will make its own choices. In absolute terms, capacity in Europe as a whole remains at its current level. This is in line with the European Technology Platform's vision for nuclear energy (SNE-TP, 2007).

Evolution of costs
To estimate how costs will evolve, learning curves have been used. The so-called progress ratio represents the cost reduction after each doubling of installed capacity. A progress ratio of 0.9, for example, means that costs fall by 10%.

Table 6 Evolution of new technology investment costs

	Progress ratio	Investments costs [€/kW] in first year 2000	2010	2020	2050
Wind (onshore)	0,90	1200			750
Wind (offshore)	0,90	2100			1250
Solar PV	0,82	6050			1600
Concentrated Solar Power	0,93	2600			1200
Fuel cells (transport)	0,81		3500		50
H_2 storage tanks (vehicles)	0,90		3		1
CO_2-capture from coal gasification (post combustion)	0,90			700	500
CO_2-capute from coal gasification (pre-combustion)	0,90			300	270

Reference scenario
Because energy conservation is one of the key priorities in sustainable energy supply, the calculation model incorporates elastic demand. This allows the reductions in demand resulting from the high fuel and CO_2 prices to be studied.

To establish the amount of energy saved, a reference scenario is needed. This assumes low fuel prices (see Table 7) and a minimal climate levy (€ 10 per tonne of CO_2).

Table 7 Energy prices in the reference scenario

$\$_{2005}$/barrel	2000	2030	2050
Oil	27	36	39
Gas	17	29	33
Coal	9	11	11

Colophon

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