ANALYSIS OF INNOVATION DRIVERS ANDBARRIERS IN SUPPORT OF BETTER POLICIES

Economic and Market Intelligence on Innovation

Integrated Innovation Policy for an Integrated Problem: Addressing Climate Change, Resource Scarcity and Demographic Change to 2030

Final Report

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Foreword

"INNO-Grips" (short for "Global Review of Innovation Policy Studies") is supporting policy makers in adopting appropriate policy responses to emerging innovation needs, trends and phenomena. It analyses framework conditions, barriers and drivers to innovation and innovation policy and offers intelligence on international developments in these fields.

Over a period of three years (2010-2012) INNO-Grips will conduct studies and organise workshops to exchange views, ideas and best practices with innovation stakeholders in order to optimise innovation policy Europe-wide. These key activities will be complemented by a news service about international innovation policy developments, covering about 40 countries worldwide, and further dissemination activities such as newsletters. Target audiences are invited to discuss the results of studies and related issues in an interactive online environment (the INNO-Grips blog). INNO-Grips is thus a platform for all stakeholders involved in the practice of innovation and in innovation policy, in particular innovation policy makers at the EU, national and regional levels; innovation intermediaries such as innovation agencies and knowledge transfer centres; innovation practitioners and academia conducting research on innovation dynamics.

Technically, INNO-Grips consists of two lots. The first one –"Innovation policy research and intelligence"– gathers evidence on innovation policy developments worldwide and analyses specific aspects and trends in detail. The second lot –"Economic and market intelligence on innovation"– analyses framework conditions (e.g. implications of socio-economic trends), barriers and drivers to innovation at firm level. This report is the first in a series of six studies in the context of the second lot which will investigate the following topics:[1]

1. Barriers to internationalisation and growth of EU's innovative companies
2. Socio-economic trends for innovation policy
3. Open innovation and other new forms of collaboration
4. Social attitudes to innovation and entrepreneurship
5. The role of multinational companies and supply chains in innovation
6. The new nature of innovation

These studies will be delivered in close coordination with the representatives of the European Commission and in close interaction with the service providers of the other PRO INNO Europe activities. All studies are of high relevance to the activities set in the context of the Flagship Initiative "Innovation Union" carried out as part of the new Strategy Europe 2020.

WIFO is the lead partner of the "Economic and market intelligence on innovation" studies and is also responsible for the coordination of activities with the European Commission. The partner institutions in this project are NIFU-Step based in Oslo, UNU-MERIT based in Maastricht, the Fraunhofer Institute for Systems and Innovation Research (ISI) based in Karlsruhe, and the Management Center Innsbruck. Greenovate! Europe will support all dissemination activities. Each study will be presented and discussed at workshops organised by the Consortium in close cooperation with the European Commission. The workshops will serve to present the findings and conclusions as well as the derived policy recommendations to a qualified audience of stakeholders, representatives of the business community, policy makers, and leading academics for external validation.

The present report focuses on an Integrated Innovation Policy for an Integrated Problem: Climate Change, Resource Scarcity and Demographic Change.

[1] See http://www.proinno-europe.eu/inno-grips-ii/page/studies for more details.

Executive summary

Mitigating climate change is probably the most pressing problem for innovation policy in the world today. An integrated policy approach is required that can address the effects of demographic change, increasing global affluence, and resource scarcity.

The goal of climate change policy is to prevent dangerous levels of global warming from increasing concentrations of greenhouse gases (GHG) in the atmosphere. In Europe, C02 from energy sources accounts for 76.7% of all GHG emissions.

In 1996 the European Commission already accepted that global warming must not exceed 2° C. Although the precise relationship between warming and dangerous warming is not known, a global average temperature increase of over 2 °C will lead to positive feedback effects that will exacerbate warming. Preventing more than 2 °C of warming requires keeping total global carbon emissions from energy sources up to 2050 below approximately 530 gigatonnes and reducing average EU energy CO_2 emissions in 2050 to approximately 1 tonne CO_2 per capita (based on the EU's 2008 population).

Innovation to replace fossil fuels with zero carbon energy is an essential part of the solution. In response to the concerns of citizens and businesses in many countries over the cost of replacing fossil fuels, several influential economists and observers have proposed a '*R&D investment model*' to solve global warming. The model proposes a five-fold increase in publicly funded R&D into zero carbon energy technologies to reduce their cost to comparable levels with fossil fuel energy. The model may have worked if substantial increases in R&D investments had been implemented a decade ago. However, it is now too late. Every year that serious action on reducing CO_2 emissions is delayed makes the problem more difficult. For example, without a global emissions trading system (where Europe can purchase emissions from developing countries), delaying serious action to reduce European emissions to 2015 would require EU emissions to fall by 12.7% per year and reach sustainable levels of 1 tonne per capita in 15 years.

To avoid dangerous climate change it is desirable for Europe to reduce CO_2 energy emissions by 30% by 2020, which would require an annual decline of 2.8% up to 2020 (compared to a decline of 1.5% per year for the current 20% reduction target). After 2020, emissions would need to decline by 5.6% per year up to 2050 (which also requires emission trading with low emission countries). This would require a concerted policy effort to manage the transition after 2020 to a much faster rate of implementation of zero carbon energy technology. This approach allows some room for a modified R&D investment model, but rapid increases in R&D investment would need to start immediately and the cost of carbon would need to be increased quickly in order to encourage investment in large scale zero CO_2 energy production.

Changes in the age, income, and size of populations influence climate change through their effect on GHG emissions. The best evidence for Europe suggests that an increase in the age cohort over 65 years of age will slightly increase GHG emissions (after controlling for other effects such as population growth) due to greater use of domestic heating and electricity. This is disappointing, since earlier research suggested a large reduction in GHG emissions from demographic ageing. Concerns over a decline in the innovative potential of older cohorts appear overstated. Europe will continue to have sufficient scientific and engineering capacity to benefit from breakthroughs in green technology that are made abroad, in the same way that Europe has been able for decades to adopt American innovations in computing and software.

Higher prices of oil and natural gas through the normal operation of markets will not solve the climate change problem. Fossil fuel reserves are too plentiful and there also exist low-cost substitution possibilities between fossil fuels (liquid transport fuels can be produced from gas and coal). This means that we cannot rely on higher market prices to greatly improve the competitiveness of renewables.

Renewables cannot take the place of fossil fuels in the short term because of costs and other constraints and neither can nuclear (nuclear power plants take 3 to 6 years to build, with planning permission taking a few years too). Given that CCS is also not a short term option, an annual reduction of 2.8% in energy CO_2 emissions up to 2020 will need to partly rely on better energy efficiency. A clear target for policy is the energy efficiency of existing buildings (new and old). The energy efficiency of new appliances is another important target.

In the absence of CCS for achieving CO_2 reductions in the short term we need to simply use less fossil fuels. This requires carbon constraining policies. A decline in carbon intensity will require rapid technological innovation to increase the efficiency with which energy is used and to replace almost all current energy production with zero carbon energy. Consequently, the EU needs to introduce an integrated set of policies to address global warming that affects technical, social, behavioural and organisational innovation across all EU countries. The policies will need to include everything from a realistically demanding level of carbon taxes to changes in regulations on buildings design, freight handling, urban design, investment in public transit, and an increase in public and private sector investment in R&D.

Clearly what should *not* be done is to subsidise the use of fossil fuels or to give away carbon emission rights for free to energy intensive sectors. Carbon leakage may provide a rationale for giving sectors exposed to carbon leakage a larger proportion of the carbon rights for free but it is important that also these sectors must buy some carbon rights. Low-cost carbon reductions from material substitution are being missed because of free distribution of carbon rights. Free allocation of carbon rights can lead to windfall gains, from selling some of these free allowances (those they do not need). Earnings from selling carbon allowances are warranted when companies make special low-carbon efforts, not when they do not.

The availability of some mineral resources may put a constraint on fossil fuel alternatives. Lithium-ion batteries for cars use cobalt, PV panels use indium and gallium, wind turbines use neodymium, fuel cells require platinum, and micro-capacitors for electric cars require niobium and tantalum – all 'critical materials' whose availability is limited.

The innovation policy implications of the critical materials issue for emerging low-carbon energy technologies are not fully clear. Market forces should generate substitutes but it is unclear whether this will happen in time and whether market-based processes will not produce a too narrow range of alternatives. Public support of research into alternatives may be warranted to widen the search for substitute materials and speed up the time by which they are available. Research could look at how to substitute scarce minerals with abundant compounds. Another solution is to stimulate recycling of critical materials.

Nanomaterials offer opportunities to create special materials whose use may help to save fossil fuel-based energy and reduce carbon emissions. Opportunities to reduce carbon emissions offered by nanomaterials should therefore be exploited. Examples of application are carbon nanofiber car and organic solar cells using nanoparticles. There are also risk issues which need to be addressed and issues of recycling.

Climate policy may benefit from a resource efficiency approach. More generally, climate policy might be able to piggy back on other issues, such as energy security, clean air policy, resource productivity, sustainable transport policy, materials policy, industrial policy etc., but non-climate policies may also erect barriers for it through the protection of national energy-intensive industries, coal industries and the car industry as well as the facilitation of car-mobility.

The fundamental problem facing innovation policy to prevent dangerous global warming is how to encourage a transition from a fossil-fuel economy to a zero carbon economy. Transitions have occurred in the past, but at a slower rate and in response to market prices. The transition to a zero carbon economy faces much larger barriers than faced in the past by other emerging technological systems, such as information technology, both because of the pressing need for a rapid transition and because the transition must confront a cheap, plentiful, and socially embedded energy system based on fossil fuels. The transition will also face negative feedback effects. As renewables provide a larger share of energy, the demand for fossil fuels will decline, leading to price falls (lower price increases for fossil fuels). Furthermore, consumers are resistant to paying more for environmentally beneficial technologies or to make significant life style changes to reduce GHGs.

The price-competitiveness problem for low and zero carbon energy can be addressed by introducing a price on carbon that is high enough to provide a market for renewables. However, a price that is high enough to have an effect is not politically viable and would require a painful economic transition. Consequently, the design of transition policies is a key challenge. For systemic change, a long-term policy effort is needed. Transitions cannot be managed from the top or through the use of economic incentives. What policy makers can do is put pressure on carbon-based systems and nurture alternatives. In the report we identify **two important paths for achieving mitigation benefits**:

1. Decarbonisation of electrical power generation and electrification of the transport sector.
2. Dematerialisation of the economy through energy efficient products (including homes) and re-use and recycling of products and waste.

Decarbonisation of the power sector means a shift to zero-carbon technologies. This can be done by the use of solar energy and other renewables, nuclear energy and CCS. Decarbonisation of the power sector implies also a phase out of fossil-fired plants. With a decarbonised power sector, greenhouse gas emissions from the transport sector can be reduced by shifting to electric propulsion using batteries and fuel cells. GHG emissions from transport can also be reduced by biofuels provided these are produced in a carbon-low way. For decarbonisation, a necessary strategy for the short-term is *getting more energy out of fossil fuels*. The use of waste heat is one strategy, district heating is another strategy. Opportunities for the use of waste heat are enormous, exceeding by far the carbon reductions that can be achieved through low-carbon power, often at negative costs. Micro-cogeneration can be used to heat single homes and can be combined into virtual power stations.

Dematerialisation is using less material, energy, water and land resources for the same economic output. Dematerialisation can be achieved through the use of light-weight products and from re-use and recycling of waste. A useful and possibly achievable policy target is the doubling of resource productivity from 2010 to 2030. When achieved, this will bring significant climate mitigation benefits. Dematerialisation is another term for resource efficiency.

These trajectories for mitigation must be combined with a trajectory of **climate adaptation**, to protect ourselves to the negative effects of climate change (storms, droughts, transient floods, reduced water availability, heat waves, vector-borne diseases, and permanent flooding from rising sea levels). Climate change presents designers, architects and planners with the imperative to create buildings and spaces that are resilient in the face of future climates. Adaptation measures are in several respects different from mitigation options in that they require specially designed solutions tailored to local circumstances. Cooperation with a group of actors has to be secured.

Controlling the climate through geo-engineering is another strategy. Different from climate adaptation geo-engineering cannot be used to micro-manage risks and involves risks of its own. There may be a role for certain forms of geo-engineering but at this moment it can only be recommended as an option for research and field trial, not for implementation.

The report develops twelve themes for innovation policy for climate protection, drawing on the literature on innovation policy and the more specialised literature on eco-innovation and energy technology policy.

The themes are, first, that *climate policy is best pursued within a green growth strategy and quality of life strategy*, rather than as an environmental policy. Doing so helps to secure a wider range of benefits and may also be a more effective way of achieving greater climate protection benefits, given that growth and quality of life are important policy goals. Integrating it in those agendas thus makes sense from the viewpoint of effectiveness and may also fulfil the useful function of bringing together these two rather separate agendas.

The second theme is that *policy should be based on identified barriers* to innovation instead on abstract notions of market failure and system failure. This requires mechanisms for learning about those barriers. To make effective policies it is necessary that government officials do not fall prey to hype-disillusionment cycles and special interests (of incumbents or newcomers). Support often has been abandoned too quickly following disappointing results or because of the need to cut spending.

The third theme is that policy should *prevent windfall gains and regulatory capture*. A danger with financial support policies (but also other types of policies) is that they generate windfall profits, in the sense that the project would also be undertaken in the absence of support. Expert opinion can be used to prevent this but in the case of fiscal support there is no ex ante check upon the additionality (effectiveness) of support. The grandfathering of CO_2 rights produced windfall profits for carbon emitters.

An additional problem is 'capture' of the grants systems by industries. Public funding for marginal improvements is a waste of public money, which should focus on technological frontiers. Improving coal should be funded

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by the private sector in response to carbon prices. An alternative funding mechanism that could be explored is the use of prizes. To work, prizes need to be specific enough to ensure that the innovation is worth the investment, but flexible in how the goal is achieved. The problem is determining the size of the prize, to optimise private investment while minimizing the cost to the public purse.

The fourth theme is about creating an *independent climate change agency*. Climate change policy needs to be developed in the public interest, which requires independent assessment of claims for and against particular options and seeing through fashionable discourse. Two types of expertise are required: 1) an analytical knowledge of the economics of innovation and the effects of policy instruments and 2) extensive knowledge of the technological options and the energy systems. This goal would benefit from an independent policy institution. An example is the independent regulatory agencies for pharmaceuticals, such as the Food and Drug Administration in the United States and the European Medical Evaluation Agency in Europe. Such an agency for climate change can assist policy makers at different government levels to deal with uncertainty and conflicting claims and evidence and to assist the continuous long-term process of adaptive policymaking.

The fifth theme is *policy mixes*. In general we need a mix of technology-specific and generic policies. Carbon trading is an example of a generic policy. Examples of technology-specific policies are RTD support for biomass gasification, sustainability criteria for biofuels, and specific feed-in tariffs and deployment targets for renewables. There is a need for push and pull policies. The bulk of investments may occur after 2025, to benefit from R&D programmes, but we also need deployment policies between 2010 and 2025 for three important reasons: 1) learning curves depend on capacity and deployment, not just on R&D, 2) policy proceeds in steps, with early steps preparing for later steps (high carbon prices can only be introduced after low carbon prices, stricter regulations can only be gradually phased in), and 3) a delay of 10 years will result in a far greater step change in investment during the following decade, placing even greater strain on the ability of supply chains to deliver.

The sixth theme is that *significantly higher levels of public R&D support are needed* (something which is widely acknowledged), although there is not enough time to rely on the R&D investment model alone, due to lead-times of 10 to 15 years (until 2020 or 2025) to develop low or zero carbon alternatives that approach the cost competitiveness of fossil fuel energy sources. Public investment in R&D for incremental improvements to existing technologies such as wind power is often unnecessary. Public investment should be primarily focused on R&D for disruptive and radical zero carbon energy technologies (it is equally important that one does not rely too strongly on long-term solutions as they may remain a long-term solution, nuclear fusion being an example of this) and on providing necessary infrastructure.

There is a *role for missions* (theme seven) but the key challenge is not to develop technologies but to get innovations adopted, which is very much a matter of economics rather than technology. The requirement of co-funding by industry is one way of making sure that the technologies to be developed will not turn out to be "white elephants". A possible model here is the public-private partnership model that is used in the German *Clean Energy Partnership* (CEP) for hydrogen and fuel cell vehicles.

The eighth theme is *policy coordination*. There is a pressing need for policy coordination across the EU, partly to ensure the effectiveness of publicly funded research and to reduce replication, in part through international and domestic cooperation. Coordination is particularly important within the EU because renewable energy sources are not equally distributed across the EU. Some countries such as the UK and Ireland have ample wind power reserves while others such as Spain have excellent sites for solar power. Other countries have poor renewable energy possibilities and will need to rely either on power from other regions (requiring an EU wide smart electrical grid) or on nuclear power. The coordination role needs to be managed by the European Commission, as the only organisation that can coordinate national efforts. Furthermore, the EC needs to set strong, credible policy commitments to encourage large scale investment by private firms. A 100% renewable power could require imports of solar power from North Africa. The EC could be the best European governmental level to organise and oversee power imports and the necessary smart electrical grid to ensure that renewable energy can reach all areas of the EU.

The choice and selection of innovation projects requires *strategic intelligence*, being the ninth theme. There is a need for strategic intelligence for smart grids, a broad concept comprising a multitude of options – to investigate benefits and viability of configurations. There is a need for critical assessment of societal benefits (including benefits in climate mitigation) because smart grids are very much 'talked up' by those interested in it. Electric mobility is another candidate for the creation of strategic intelligence, being a critical innovation for climate protection. Strategic intelligence may also be created for soft innovations, such as intermodal personal transport, based on the combination of different modes of transport.

It is desirable that a *broad portfolio of options for climate mitigation* is supported (theme ten), to widen the search process – all low and zero carbon energy technology needs to be further developed. This involves funding blue-sky exploratory research into a diversified portfolio of research projects. Unfortunately, the global financial crisis has diverted the EC's SET Plan for more R&D to more of a focus on regulations and market mechanisms for pricing emissions, and dealing with the problem in that way. Pricing mechanisms are unlikely to be sufficient, with extensive public R&D necessary. In any case, the SET Plan was not ambitious enough, proposing annual expenditures of 7.5 billion euro in R&D support from the private and public sector combined, when the public sector should be contributing between 5 and 11 billion euro per year alone.

Uncertainty as to the effects of policy instruments call for *policy learning* (theme eleven). Lessons learned by executive agencies and evaluators should be disseminated internationally. For achieving a transition it is important that policy learning evolves with the development of new technology innovation systems. The Dutch energy transition approach stands out as a useful model in this respect.

There is a *need for international policies* (theme twelve) to fund zero carbon energy in developing countries and to prevent the destruction of carbon sinks. Obligations are best combined with the use of an earmarked carbon tax to generate funds for research and infrastructure in developing countries and to pay for the preservation of existing carbon sinks such as tropical forests and undisturbed savannah soils. Past programmes have been too small and resulted in minimal gains (for example the CDM mechanism). Creating funds is the relatively easy part. The more difficult part is ensuring that the funds are spent efficiently and not diverted to other purposes. The money from a carbon tax or from pooling resources may also be used to fund collaborative research into low-carbon technologies and to support multi-billion euro innovation programmes. A tax on carbon imports will avoid carbon leakage and prod non-Annex 1 countries into action.

Innovation policy recommendations are thus many. It is important that policy should not be viewed purely in instrumental terms but as a trajectory in itself. To successfully carry out an energy transition will require a continuous process of adaptive policymaking. The need for information in the policy process puts a premium on feedback and flexibility in the design of strategies and policies for energy transitions. It also requires the development and strengthening of tools for an analysis of the kinds of capacities which need to be built and the variety of pathways and policies through which this has and is being undertaken.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF BOXES

1 INTRODUCTION

Two main trends will disrupt the economy of the European Union over the next few decades. The first trend consists of a pressing need to mitigate climate change and address possible resource constraints. This has been termed a 'super wicked' problem because of its scope, complexity, and potential costs (Adler, 2010). The second trend concerns global population changes, which include a demographic shift to older population structures in Europe and abroad and the growing share of better educated, middle income populations in developing countries.

Both trends could create a third problem: a decline in the availability (at a reasonable price) of key resources. On a global scale, the growth in the affluent share of the population of Asia and Latin America will increase demand for energy, clean water, agricultural products, forestry products, and minerals at the same time as increasing drought and climatic variability will make it more difficult to provide clean water and essential natural resources such as food, feed and fibre (OECD, 2009). One consequence is an expected long-term increase in the price of natural resources up to 2015 and possibly longer (OECD, 2008).

Changes in the age, income, and size of populations also directly influence climate change through their effect on greenhouse gas (GHG) emissions. Population ageing in Europe could reduce incomes and consequently consumption, making it easier for Europe to reduce its GHG emissions (O'Neill et al, 2010). However, an older population structure in Europe has raised fears that the innovative capacity of Europe could decline, reducing the competitiveness of European firms and their ability to reduce GHG emissions. The ability of European governments to solve this perceived problem through attracting well-educated immigrants is likely to fall, due to growing affluence abroad (reducing the pressure to immigrate) and by the fact that several of the main source countries in East Asia for well-educated immigrants are also undergoing a demographic shift to older populations. European populations could also oppose greater immigration if equitable allowances for greenhouse gas emissions (GHGs) are based on the European Union's share of the global population in 2008 or 2010.[2] Under this condition, any population increase would require a decline in per capita emissions, and possibly per capita living standards.

Innovation will be essential to addressing the challenges posed by these two megatrends and to the ability of Europe to take advantage of the opportunities that these two trends will create. This will include not only public and private sector innovation to provide an effective solution to climate change, but also organisational and technical innovation to substantially improve the efficiency of services, to conserve energy, particularly for heating, and to develop technologies to provide zero carbon energy, improve agricultural production, and the quality of life in later years.

Predicting socio-economic trends over the next five to twenty years is difficult, particularly when these trends both drive and are driven by government policy and society in an interactive process. Due to this complexity, a successful innovation policy to shape our future must be able to flexibly manage economic transitions and multiple possible outcomes, due to unpredictable technological developments or alternative political decisions. Given the extent of the challenges, an innovation policy must also be integrated, both across Europe and across applications.

Chapter Two examines the challenge of reducing greenhouse gases (GHG) in order to prevent dangerous climate change. Although the timeline in this report is to develop policy up to 2025, a longer term perspective up to 2050 is required to determine how much progress is required over the short and medium term in order to be on track for meeting longer term goals. The Chapter gives several scenarios for reducing GHGs, using a business as usual (BAU) approach and different time delays before the start of effective action to reduce CO_2 emissions. Chapter Three reviews a range of proposals for innovation policy to address the challenge of climate change. Chapter Four examines the effect of demographic change in Europe on climate change. Chapter Five examines the implications of growing resource scarcity for climate change mitigation. Chapter Six offers a classification of innovation and outlines the transition perspective on sociotechnical change which is applied to the problem of making a transition to a

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[2] The EU is already suffering a braindrain of highly skilled workers.
http://ec.europa.eu/euraxess/pdf/research_policies/MORE_final_report_final_version.pdf

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low-carbon economy. Chapter Seven examines the innovation policy issues for mitigation, adaptation and geo-engineering and makes recommendations for innovation policy.

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2 THE CHALLENGE OF CLIMATE CHANGE

2.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC, 2007a) concludes in its latest report on climate change that anthropogenic GHG emissions are already having wide ranging impacts on Europe (see p. 546 of IPCC, 2007a, for examples of such impacts), but that harmful effects are expected to worsen over time with increasing global temperatures. Nevertheless, without action to reduce GHG emissions over the near future, the IPCC predictions for Europe include an increasing incidence of winter floods, flash floods, coastal flooding from rising sea levels, droughts, intense heat-waves, and forest fires. The secondary effects include greater exposure to vector- and food-borne diseases, shifts by region in the distribution of forests and crop suitability and productivity (with increases in some areas and decreases in others), water availability and water stress. Natural ecosystems and biodiversity could also suffer if many species are incapable of rapidly adapting to changing environmental conditions.

The economic sectors that are most likely to be affected by future climate change in Europe are agriculture, energy and tourism (IPCC, 2007a). Water demand for agricultural irrigation will increase in Southern Europe and so will crop-related nitrate leaching. Although the demand for winter heating will decrease, the demand for summer cooling will increase. This will cause peak electricity demand to shift in many locations from winter to summer. Winter tourism will suffer in mountainous regions from a lack of snow but increase in the Mediterranean. However, summer tourism in the Mediterranean will decline.

These effects of climate change are mild compared to the predicted effects of an increase in global temperatures of 3 °C compared to pre-industrial levels. At this level, the global climate could pass several tipping points that could lead to serious and possibly irreversible changes. To prevent dangerous climate change, in 1996 the European Commission accepted that global warming must not exceed 2 °C. Based on research suggesting that atmospheric CO_2e levels must not exceed 450 ppm to limit warming to 2 °C, the EU committed in 2007 to decrease GHGs by 60-80% from 1990 levels by 2050, and by 20% by 2020 (Council of the European Union, 2007). There has also been recent discussion of revising the latter goal to a 30% decline in GHGs compared to 1990.

However, there are warnings that these goals could be insufficient. Even an 80-95% emission reduction within the developed countries gives only a 50% chance of keeping the global temperature from rising more than 2 °C (Den Elzen et al., 2008, or IEA, 2009).[3] Further, a number of leading climate scientists currently believe that we need to decrease atmospheric CO_2 concentrations from the current 388 ppm to 350 ppm or below (Girardet and Mendonca, 2009). This would require not only decreasing emissions drastically, but also removing some of the already existing greenhouse gases from the atmosphere. A short review of the scientific evidence for limiting global warming to no more than 2 °C in order to prevent dangerous climate change is provided in Box 2.1.

Box 2.1 The 2-degree target for global warming

The range of projected average global temperature increases due to anthropogenic GHG emissions is 2°-7°C by the year 2100, depending on the amount of CO_2 and other GHGs emitted this century (UNSW, 2009). Temperatures could continue to increase for a century after the peak in GHG emissions due to the slow rate at which the ocean warms (UNSW, 2009) and the gradual melting of ice sheets (Hansen et al, 2008). Meinshausen et al. (2009) calculate that under lower GHG emission scenarios, global temperature could peak by 2100. The rise from pre-industrial levels until now is about 0.8 degrees. Furthermore, even if anthropogenic CO_2 emissions fell to zero later this century,

[3] The EU's goal for a new post-Kyoto climate deal is that developed countries should cut their emissions by 80-95% from 1990 levels by 2050. See http://ec.europa.eu/environment/climat/pdf/copenhagen/Info%20sheet%20key%20objectives%20final.pdf, viewed on 29/06/10.

the temperature increase from peak CO_2 levels would only decline slightly over the following thousand years, due to the slow removal of CO_2 from the atmosphere through natural processes (Solomon et al, 2009).

Climate science has not yet been able to accurately identify a 'safe' level for a long-term increase in the global average temperature, due to uncertainty in the equilibrium amount of warming at a given level of CO_2 concentrations in the atmosphere.[4] The worst case outcome is a catastrophic melting of both the Greenland and Antarctic ice sheets, which would cause a 65 metre increase in sea levels. This occurred in the early Cenozoic when atmospheric CO_2 concentrations were somewhere between 1000 and 2000 ppm (Hansen et al, 2008). The Antarctic ice sheet began to reform once atmospheric CO_2 levels fell below approximately 500 ppm, suggesting that sustained CO_2 concentrations above 500 ppm would result in a gradual melting of all ice sheets (Hansen et al, 2008). However, this would require centuries if not millennia of CO_2 concentrations possibly well above 500 ppm. Nevertheless, this is a plausible outcome if CO_2 emissions continue to increase by 2% per year for another 30 to 40 years and if no actions were taken to remove CO_2 from the atmosphere.

At lower levels of global warming, the difficulty in determining the 'safe' level is due to uncertainty over tipping points for undesirable effects. A tipping point is a level of global warming that sets off qualitative changes in global or regional climate. Exceeding some tipping points lead to increased fast and slow positive feedback effects that further amplify CO_2 levels, thereby increasing global warming. Passing other tipping points will not increase global warming, but could result in significant deleterious changes in regional climates. Not all of the deleterious effects of global warming derive from tipping points. A gradual increase in ocean temperatures increases the rate of evaporation which increases water vapour in the atmosphere. Since water vapour is a major GHG, this further increases global warming.

Hansen et al. (2008) and Lenton et al (2008) evaluate a large number of tipping points in the climate system. A relatively fast positive feedback effect is the summer melting of Arctic sea ice, which increases global temperatures by warming the Arctic Ocean. Some of these positive feedbacks, such as the melting of Arctic sea ice in the summer and a gradual melting of the Greenland Ice Sheet are expected to occur with sustained global warming under 2 °C. Several dangerous tipping points start at 3 degrees or more of warming above the 1980 – 1999 average temperature. These include dieback of the Amazon rainforest (which would release 100 Gt of CO_2), melting of the West Antarctic ice sheet, and methane emissions from arctic permafrost and shallow arctic seas (Lenton et al, 2008; Shakhova et al, 2010), although the effect of methane emissions is limited to approximately a decade, as methane reacts with air to form carbon dioxide (Kerr, 2010). However, this added CO_2 in the atmosphere would contribute another 0.5 °C to the long term temperature increase. Climate disruptions such as monsoon patterns that could substantially reduce crops in South East Asia could begin with 3- 6 °C of warming.

Hansen et al. (2008) differentiate between a tipping point and a point of no return (i.e. irreversible change), and stress that a tipping point can be temporarily exceeded without passing a point of no return. This is an important distinction, since the ability to temporarily overshoot tipping points could be essential to preventing dangerous global warming, as long as actions are taken in time to reduce global temperatures by actively removing CO_2 from the atmosphere. Without such actions, elevated levels of CO_2 would remain in the atmosphere for millennia (Solo-

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[4] We do not report results here for all greenhouse gases because most other GHG gases (there are a few exceptions) such as methane do not remain in the atmosphere for centuries, as with CO_2. Therefore, the long-term effect of atmospheric greenhouse gases on global warming is primarily due to CO_2 concentrations.

[5] Climate researchers use models to estimate the degree of uncertainty around the expected temperature increase for an increase in atmospheric CO_2 levels. The IPCC (2007) estimates that doubling CO_2 concentrations from 280 ppm in the pre-industrial level to 560 ppm could increase average temperatures by between 2.5 and 4 degrees. Hanson et al disagree, noting that this estimate only takes fast feedback effects (such as the albedo effect from melting summer Arctic sea ice) into account. If slow feedback effects (such as ocean thermal response) are also considered, the average global temperature from a doubling of CO_2 concentrations (from 280 to 560 ppm) could be somewhere between 3 and 6 degrees. On this basis, Hanson et al propose a lower safe limit of 350 ppm.

[6] A synthesis report of a major climate change conference in Copenhagen in March 2009.

[7] Oppenheimer and Alley (2005), cited by UNSW (2009), page 49.

mon et al, 2009).

There is disagreement among climate scientists over the level of atmospheric CO_2 concentrations that would prevent more than a 2 °C increase in global warming. The IPCC (2007d) estimated that atmospheric CO_2e concentrations need to be kept below 450 ppm to 550 ppm to keep the temperature increase within 2-3 °C. More recent research suggests that either a lower level of CO_2e concentrations is needed to prevent more than a 2 °C temperature increase, or that dangerous climate change will occur at less than a 2 °C temperature increase.

Hansen et al. (2008) argue that an atmospheric CO_2 level of 450 ppm (corresponding to appr. 550 ppm CO_2e) is too high, since it is based on models that did not include slow positive feedback effects.[5] They conclude that the atmospheric level of CO_2 must be kept at or below 350 ppm to limit warming to no more than 1.7 °C above pre-industrial levels. This would require removing CO_2 from the atmosphere. Rockstrom et al (2009) similarly propose a safe level at 350 ppm, but note a possible maximum of 550 ppm. Ramanathan and Feng (2008) argue that 2005 greenhouse gas levels already commit the world to 2.4 °C of warming, once the cooling effect of aerosols from air pollution is removed. Smith et al. (2009) update the IPCC third assessment of 2001 and conclude that smaller increases in temperature are now estimated to lead to larger negative consequences. Similarly, Richardson et al. (2009) [6] assess three factors in an analysis of the 'safe' level of increase in global temperature: the negative effects for humans and ecosystems of different levels of climate change, the negative impacts that societies are willing to tolerate, and the levels of climate change that might cross certain tipping points. They conclude that dangerous climate change could appear at temperature increases below the 2 °C target.

These results generally support the policy of the European Union, which is to limit global warming to no more than a 2 °C increase over the average global temperature in the mid 19th century, although with several caveats. First, even a 2 °C increase will cause serious disruptions to some parts of the globe and if sustained for several centuries, it could cause a dangerous 6 metre increase in ocean levels.[7] Smaller low-lying island states have called for no more than a 1.5 °C increase. Second, the trend in climate science is to identify increasing risks at less than a 2 °C increase in temperature. Third, the relationship between atmospheric CO_2 levels and temperature increases is not known precisely. These three caveats show that there is a high level of uncertainty around the safe level of CO_2 emissions. Meinshausen et al (2006; 2009) partly address the uncertainty by calculating the probability of exceeding the 2 °C increase at different atmospheric concentrations of CO_2.

A remaining issue is the amount and type of a temporary overshoot that is possible. The IEA's (2008) '450 scenario' allows the atmospheric CO_2e concentration to temporarily exceed the 450 ppm level, reaching 550 ppm by 2075, and declining to 450 ppm by 2200. Based on the data presented by Solomon et al (2009), this is only realistic if both anthropogenic non- CO_2 and CO_2 emissions fall to zero in 2075. Furthermore, an overshoot of this level could already pass one or more dangerous tipping points as the predicted temperature increase at 550 ppm would be 3 °C, making it difficult to reduce global temperatures back to the limit of a 2 °C increase. Overshoots may not be possible unless they are combined with remedial actions to rapidly reduce atmospheric CO_2 levels.

2.2 The R&D investment solution to climate change

The European Union's goal for a 20% fall in GHG emissions by 2020 and an 80% decline by 2050 are not particularly helpful in informing innovation policy because they fail to incorporate the scale of the problem, which depends on the timeline for how much GHG can be emitted each year, and if the proposed decline is sufficient to prevent dangerous global warming. What we need to know is how far GHG emissions will need to fall each year to prevent dangerous warming of more than 2 °C.

Research on what needs to be done to keep global warming within a 2 °C limit identifies the difficulty of the challenge. Rogelj et al (2009) conclude that national 'position statements' on actions to reduce emissions, made before the Copenhagen summit in 2009, were too weak, in total, to limit global warming to 2 °C. In the end, the Copenhagen meeting did not make any firm commitments at all. On similar lines, Anderson and Bows (2008) conclude that it is simply too difficult to limit warming to 2 °C, based on existing policy mechanisms, and that warming of 4 °C is more likely. This level of warming would put the world in dangerous territory.

In the face of these problems, scholarly discussion of innovation policy to address global warming has become considerably less sanguine about the possibility of using emission trading schemes, carbon taxes, or a cap on emissions to reduce GHG emissions. This shift in attitude is partly due to an acceptance of the political difficulty of implementing *effective* carbon taxes or emission trading schemes. This would require carbon taxes of $180 to $300 per tonne up to 2030, increasing to over $600 a tonne by 2050 (IPCC, 2007). These mechanisms or level of taxes, which provide incentives for private sector R&D investment, are politically unpalatable in many countries, including Canada, Australia and the United States, because of resistance by both industry and citizens (Shellenberger and Nordhaus, 2010). Citizens in many countries have not supported the necessary level of carbon taxes because of concerns over cost increases for energy and goods and possibly painful shifts in lifestyles.[8]

An alternative proposal that is gaining favour among some innovation scholars is for governments, often combined with private sector investment, to invest heavily in R&D to develop low and zero carbon energy sources that are cost competitive with fossil fuels, the major source of GHGs. Under this proposal, carbon taxes are either avoided entirely or kept to a low level that is just sufficient to spur private sector investment in low carbon energy sources. Once low and zero CO_2 sources approach cost effectiveness with fossil fuels, market competition, combined with low carbon taxes, will be sufficient for reducing fossil fuel energy use. The necessary increase in Government R&D is unknown with certainty, but Shellenberger and Nordhaus (2010) propose an American contribution of 30 billion per year. This is an eight-fold increase in the $3.9 billion spent by the US government on improved energy technologies in 2009 (IEA, 2009). It could be fully funded by a 5.7 cents per litre tax on American gasoline sales.[9]

Variants of the R&D investment model to address global warming have been supported by Adler (2010), the Copenhagen Consensus Center (2009), David et al (2009), Galiana and Green (2009), Friedman (2010), Lomborg (Jowit, 2010), and Shellenberger and Nordhaus (2007). Under this 'R&D investment model' scenario, increases in energy costs are minimized, enabling a relatively painless shift from fossil fuels to low and zero carbon energy sources – albeit ten or more years into the future.

Another presumed advantage of an 'R&D investment model' is that it would avoid the need to invest in short-term expensive solutions, such as replacing coal electrical generation with natural gas, only to be forced to replace natural gas a decade later with a technology that offers lower carbon emissions. David et al (2009) comment that implementing today's most efficient energy technologies 'could prove to be more costly than delaying investments until significantly improved technologies emerge'. Gans (2009), in a model of capital investment in energy production, shows that rapid increases in the requirement for low carbon energy could have the perverse effect of blocking private sector R&D into technologies that could reduce carbon emissions from fossil fuel use. This suggests that we would be better off if governments and the private sector invested heavily in R&D today to develop more cost effective zero CO_2 sources or mitigation methods for fossil fuel energy sources. Three conditions must be met for the R&D investment model to have a chance of success:

1. Governments and business must make substantial investments in R&D for low and zero carbon energy technologies.
2. The lead times for scaling up new technology so that they are cost competitive must be acceptable.
3. We must have adequate time for the R&D investment model to succeed.

The next section examines the first two conditions, while the following sections look at the time available.

[8] A lack of citizen support is also due to widespread media misinformation on the science of climate change and a lack of knowledge on the future risks and costs of global warming.

[9] In 2009, 138 billion US gallons of gasoline were sold in the United States, equivalent to 522.3 billion litres.

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Enterprise and Industry

2.2.1 Investment in relevant energy technology R&D and lead-times

We are unaware of a reliable data source for the amount that businesses are investing in energy technology R&D. In contrast, the IEA provides time series data for R&D investments in relevant energy technologies for most member states of the European union plus other countries that are members of the OECD. There are four main categories for energy R&D that are relevant to reducing CO_2 emissions: renewable (wind, solar, bioenergy, geothermal, etc), power transmission and storage technologies such as smart grids and batteries, hydrogen and fuel cells, and energy efficiency. Figure 2.1 gives total government R&D investments for each technology category between 1998 and 2009. R&D investments increased rapidly from 3 billion USD in purchasing power parities (PPP) to 5.24 billion in 2008. The rapid increase in 2009 to almost 8 billion USD is due to a one-off increase in spending under the American Recovery and Reinvestment Act (ARRA). This is highly unlikely to be repeated. The trend line between 2003 and 2008 suggests that total expenditures should pass 6 billion in 2010 without the ARRA.

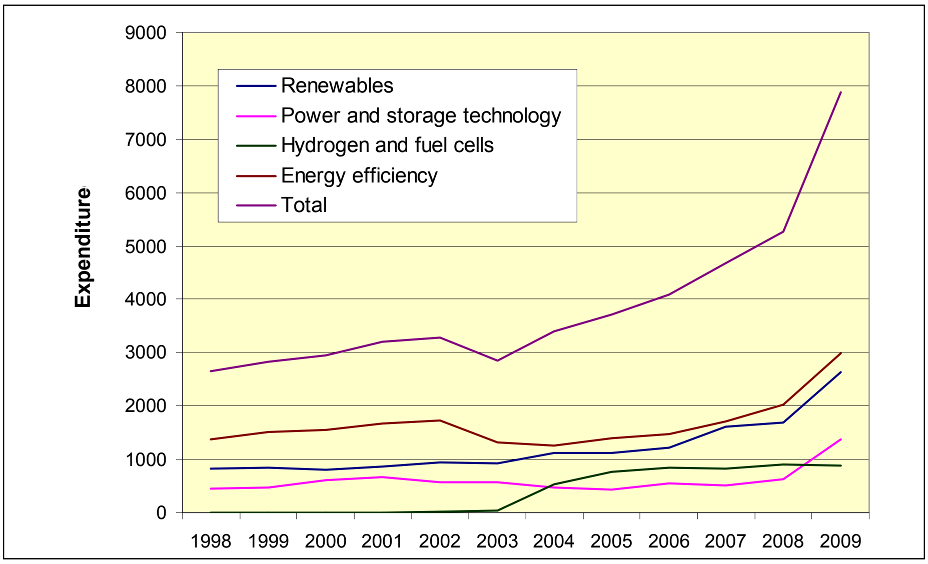

Figure 2.1 Total IEA Government expenditures on relevant energy technology R&D (million 2009 USD PPP)

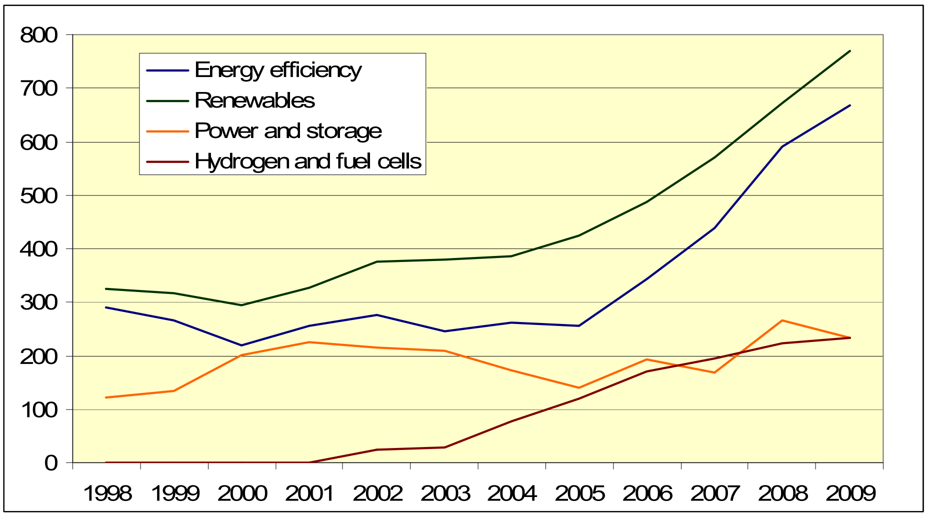

Figure 2.2 Total European Government expenditures on relevant energy technology R&D (million 2009 USD PPP).
Source: IEA, 2010

The equivalent results in Figure 2.2 (note that Figure 2.2 does not provide a total) for Europe show a long and sustained positive trend for energy efficiency and renewables. The total 2008 expenditures for Europe of 1.755 billion is 33.5% of the total IEA reported expenditures of 5.2 billion, showing that European Governments make a significant contribution to energy R&D.

However, other experts suggest that that Government expenditures on energy R&D need to increase to between 20 and 45 billion per year (IEA, 2010). The European share would therefore be expected to increase to between 7 and 15 billion USD. This should be possible, although it may be difficult to scale up research within a few years.

The second requirement is for energy R&D to lead to rapid improvements in the cost competitiveness of low and zero carbon energy sources compared to fossil fuels. Table 2.1 provides estimates for solar, wind, and bioenergy.

Table 2.1 Year to reach competitiveness with coal electrical generation

Energy type	Description	Year
Solar	CSP (concentrating solar power)	2015 – 2030, depending on region
Solar	Photovoltaic panels	2015 – 2020 in sunniest regions, 2035 in intermediate zones
Wind	Inshore	2010 (already competitive in best sites)
Wind	Offshore	Up to 2025, depending on location
Biodiesel (algae)	Using CO_2 stream from coal-fired electrical plants	2020 – 2025
CCS	Carbon capture and storage	?

Source: Kovacevic and Wesseler, 2010; Balagopal et al, 2010, Ummel and Wheeler, 2008

Wind in optimal off-shore locations is already price competitive with electricity produced by coal generation plants and photovoltaic panels and concentrated solar power (CSP), again in optimal locations, could be cost effective by 2015, although the range of estimates is up to 2035. In general, an average estimate is a lead-time of between 5 and 15 years. However, all of these estimates assume subsidies in the coming decade from carbon taxes or other mechanisms. For instance, Ummel and Wheeler (2008) estimate a subsidy of 20 billion USD over 10 years to reduce the cost of CSP, although this amount of subsidy should be feasible. Subsidies or other mechanisms including feed-in tariffs, quota systems or carbon taxes are required to promote learning by doing through experience with commercial production and scaling up. Otherwise, the expected time for cost competitiveness will be much longer. Conversely, the estimates do not include the effect of declining fossil fuel prices over time due to a fall in demand and technical improvements, both of which would reduce the cost of fossil fuel electrical generation in comparison with zero carbon energy sources. Consequently, it could take a very long time for low or zero CO_2 energy sources to approach cost competitiveness with fossil fuels without subsidies or a carbon tax.[10]

Under a best case scenario, we assume that Governments will increase investment in energy R&D by five to eight times, separately increase funding for pilot plants to gain experience with scaling up, and that low and zero carbon energy technologies will approach (although not reach) cost competitiveness with fossil fuel electrical generation within 10 to 15 years. The remaining question then is: Do we have enough time? Can we delay serious action to reduce energy CO_2 emissions until 2020 to 2025?

[10] There is also an unknown risk that some of the estimated time lines are biased by an interest in promoting renewables. The lower end estimates should therefore be assumed to be best case estimates.

European Commission
Enterprise and Industry

2.3 How much time do we have?

The success of the R&D investment model depends on the amount of time available to reduce global CO_2 emissions. This depends on the annual rate at which CO_2 emissions decline, the starting level of CO_2 emissions, and the amount of CO_2 emissions that can be released without exceeding a 2 °C temperature increase.

2.3.1 Current emission levels

The Kyoto Protocol required developed countries to reduce their GHG emissions by an average of 5.2% between 1990 and 2012, with the goal of stabilizing global emissions of GHGs. The Protocol has only been partly successful, due to a large increase in GHGs in developed countries such as Australia, Canada and the United States. Global CO_2 emissions, accounting for approximately 80% of GHG equivalents, increased from 21.12 Gt in 1990, to 23.72 in 2000 and to 30.38 Gt in 2008, although emissions in many Annex 1 countries (39 signatories from developed countries) have declined.[11] On average, global CO_2 emissions have increased by slightly over 3% per year between 2000 and 2008. If this rate increased until 2050, atmospheric concentrations of CO_2 would reach 1260 ppm.

Table 2.2 gives emissions data between 1990 and 2008 for the EU-27 and for the United States. In both regions, CO_2 and total GHG emissions have declined slightly between 2000 and 2008. Most of the decline in the United States is due to high fuel costs in the United States in 2007, which reduced consumption. CO_2 emissions in both the United States and Europe are expected to continue to decline in the near-term future due to the effects of the global financial crisis, but emissions could rise again in the future in the United States, or the rate of decline in the EU could shrink.

The results in Table 2.2 show that CO_2 emissions from energy is the largest source of total GHG emissions, accounting for 76.7% of total 2008 GHG emissions of 4.94 Gt in Europe and 80.1% of total GHG emissions for the same year in the United States of 6.96 Gt. Energy uses also contribute to the lion's share of total 2008 CO_2 emissions: 92.6% for Europe and 94.1% for the United States. Other GHGs (row 2 in Table 2.2) account for 17.2% of total 2008 GHG emissions in Europe and 14.9% of GHG emissions in the United States. Agriculture accounts for 42.5% of the other GHG emissions in the United States in 2008.

Both the EU-27 and the United States have substantial carbon sinks from land use changes which absorb CO_2 emissions. This is the opposite of the global situation, where land use changes contribute to 18.1% of CO_2 emissions, for instance from forest clearance. Carbon sinks in the United States remove almost as much CO_2e from the atmosphere each year as added by other GHGs. The sinks are mostly due to land-use changes which have increased forest cover. Carbon sinks are less significant in Europe, largely due to limited forest cover, accounting for approximately half of other GHG emissions.

[11] Excludes emissions from non-CO_2 greenhouse gases, but these have increased as well. Data for 1990 and 2000 are from the World Resources Institute, Climate Analysis Indicators Tools, CAIT.WRI.org. Data for 2008 are from the US EPA, 2010.

Table 2.2 GHG emissions1 by the EU-27 and the United States in Gigatonnes (Gt)

	EU-27			United States		
	1990	2000	2008	1990	2000	2008
1.Total CO_2	4.401	4.112	4.089	5.101	5.977	5.921
Energy CO_2	4.077	3.818	3.787	4.736	5.593	5.573
2. Other GHGs[2]	1.166	0.927	0.851	1.026	1.067	1.036
3. Total GHGs (CO_2e)	5.567	5.039	4.940	6.127	7.044	6.957
4. Sinks	-0.353	-0.408	-0.418	-1.022	-0.7633	-0.941
5. International transport fuels[3]	0.175	0.313	0.310	0.112	0.099	0.135
6. Energy CO_2 share of total GHG	73.2%	75.8%	76.7%	77.3%	79.4%	80.1%
7. GHG per capita (t CO_2e)	11.8	10.2	9.9	24.6	25.0	22.9

1: GHG emissions listed by the UNFCCC (United Nations Framework Convention on Climate Change). Other GHGs that destroy ozone (halocarbons and halons) are not included as they are subject to the Montreal Protocol to limit industrial production of ozone-destroying chemicals. One gigatonne = 10^9 metric tonnes.

2: In CO_2 equivalents. Includes methane, nitrous oxides, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6). Over a one-hundred year time horizon, the global warming potential compared to CO_2 is 21 times higher for methane, 310 times higher for nitrous oxides, between 140 to 11,700 times higher for HFCs (depending on the chemical), and 23,900 times higher for SF_6.

3: International bunker fuels for aviation and maritime shipping. These emissions are excluded from the total GHG results in # 3.

Sources: Data for the United States from US EPA, Table ES-2, Executive Summary, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008, April 15, 2010. http://epa.gov/climatechange/emissions/usinventoryreport.html

Data for the EU-27 from www.eea.europa.eu/themes/climate/data-viewers.

2.3.2 Running to stay in the same place

As a first step, global GHG emissions need to stabilize, with no annual increase. Since almost all countries maintain a goal of increasing economic growth, stabilization will not occur unless the GHG intensity of economic production (the amount of GHG emissions per unit of GDP) declines. The necessary degree of decline for a stabilization of GHG emissions can be estimated from a modified version of the IPAT equation (Jackson, 2009), where:

$I = P * A * T$

I = impacts, or GHG production
P = population
A = affluence, in per capita incomes
T = Technology, or the carbon intensity of the economy(GHG emissions per unit of income).

To date, the main policy approach, both within Europe and across the world, is to improve technology so that the GHG intensity of economic activity declines, while increasing economic growth (A) and stabilizing the population (P). Stable emissions will occur when the rate of decline in T equals the growth rate for P + A. This requires an absolute decoupling between the economy and GHG production.

Globally, an absolute decoupling between economic growth and GHG production has not occurred, as shown by the continued increase in GHG and CO_2 emissions. The value of *T*, or the amount of GDP per kg of CO_2 production) has grown by 0.7% per year globally, *P* by 1.3% and *A* by 1.4% over the past decade. This estimates an annual growth in GHG of 2% per year (1.3 + 1.4 – 0.7), which is less than the observed level. Even with a growth of GHG of 2% per year, the value of T would need to increase almost four-fold to 2.7% per year to stabilize GHG production at the 2010 level. This is the rate of change in economic efficiency that would be required to stabilize global GHG levels – the running speed for efficiency improvements in order to stand still in terms of GHG emissions, given average increases in population and GDP. The rate of efficiency improvements would need to increase faster than this to reduce global GHG emissions to 1990 levels.

The data presented in Table 2.2 show that total GHGs have declined, in absolute terms, in the EU-27 since 1990, but not in the United States. In respect to GHGs, a recent report suggests that the observed decline in GHG emissions in several EU countries such as the UK is partly artificial and due to shifting consumption from domestically produced high GHG goods to importing these goods from abroad (Jowit, 2010). The same effect is highly likely to have occurred in other industrialised countries such as the United States and Canada. The effect of imports on GHG emissions is not covered under the Kyoto Protocol.

The effect of imports can be significant, as well as national differences in economic structures. For example, if the world produced GDP as efficiently as Switzerland (with $9,000 GDP per tonne of CO_2, compared to $400 in China and $2,000 in the US and Australia), then CO_2 emissions could be reduced by two-thirds. Yet this is not realistic, since Switzerland does not produce many of the energy intensive materials that it uses, such as iron ore and other minerals, and it has ample supplies of low carbon hydro-electric power. On a global scale, only a few countries could replicate the experience of Switzerland.

Standing still, with no increase in GHG emissions would be an important step on a global scale, but it is not enough. Most studies show that global GHG emissions need to decline by 85% to 95% of 1990 levels by 2050 to prevent dangerous global warming. But the large range in GDP per unit of CO2 emissions does show that the technology for making a substantial start in reducing GHG emissions already exists.

2.3.3 Sprinting to reduce Global GHG emissions

Preventing dangerous climate change requires innovation to reduce GHG emissions. The reduction must be global, since dangerous warming will occur even if the OECD countries produce zero GHG emissions, as long as other major emitters such as China, India and Latin America combine high economic growth with rapidly growing emissions.

But how far and how rapidly will GHG emissions need to fall? We look at this issue below, using several scenarios for CO_2 energy emissions. We ignore other GHG emissions at this point, both by assuming that they can be partially accounted for through carbon sinks and because of the considerable role of agriculture in their production. The two main agricultural sources include methane produced by ruminant livestock (the source of 13.6% of other GHGs in the United States in 2008, greater than all CO_2e emissions in the United States from international transport) and through nitrous oxides from soil management. Innovation can have a significant role in reducing agricultural GHGs, but at this time we follow standard practice by focusing on CO_2. In addition, as explained further in the next section, the scenarios are limited to energy sources of CO_2 which account for over 90% of all CO_2 emissions in the EU.

2.3.4 The CO_2 budget

The first step in determining how far EU emissions will need to fall is to estimate the global amount of GHGs that can be emitted between 2011 and 2050 while keeping the global average temperature increase below 2° C. For CO_2, this permissible amount of emissions is called the global CO_2 budget.

Every year, human activities add GHGs to the atmosphere and every year some of the GHGs are removed, either through chemical reactions in the atmosphere (ie. methane) or through capture of CO_2 by land and ocean sinks. However, the additional GHGs that are added to the atmosphere exceed the rate at which they are removed. For CO_2, this creates the observed trend of rising atmospheric CO_2 concentrations from 280 ppm in the 1800s to 388 ppm today. Dangerous global warming is expected to develop once atmospheric concentrations of CO_2 surpass tipping points (see Box 2.1) that either lead to increased positive feedback effects that amplify global warming or which have deleterious effects on agricultural production or human settlement.

Meinshausen et al. (2009) estimate the global CO_2 budget between 2000 and 2050 for different levels of probability for exceeding a 2 °C increase in the global average temperature. For energy CO_2 plus land use changes that remove CO_2 sinks, they estimated that limiting global emissions from these two sources to 1,000 Gt would give a 25% probability of exceeding a 2 °C temperature rise, while global emissions of 1,437 Gt would give a 50% probability of exceeding a 2 °C temperature increase.

European Commission
Enterprise and Industry

It is important to note that these estimates for the global CO_2 budget *exclude other non- CO_2 GHGs such as methane and nitrous oxide*, produced primarily by agriculture, and a group of gases, including fluorinated compounds, produced by industry. On a global scale, these non- CO_2 gases contribute approximately one-third of all GHGs. When all GHGs are combined, the GHG budget between 2000 and 2050 is 1,500 Gt of CO_2e for a 25% probability of exceeding a 2 °C temperature rise and 2,000 Gt for a 50% probability.

We follow other budgetary approaches by concentrating on energy related CO_2 (see e.g. WBGU, 2009). The justification for this is partly scientific and partly due to differences in the policy context of non-CO_2 GHGs. [12] The scientific justification is due to the fact that energy related CO_2 accounts for 92% of European CO_2 emissions, with the non- CO_2 GHGs primarily a problem in developing countries. Furthermore, CO_2 can remain in the atmosphere for thousands of years, whereas most other GHGs, such as methane and nitrous oxides, are comparatively short-lived.

There are also two policy reasons for focusing on energy related CO_2. First, the factors that create other GHGs differ from those that create energy CO_2 emissions, so that the appropriate innovation policies will need to differ. The WBGU (2009) suggests that separate global agreements be made for land-use change related CO_2 and fluorinated GHGs. The EU could rapidly increase the size of its land use sink by reducing agricultural subsidies and encouraging unproductive agricultural land to be returned to forest. Second, there may be better technical opportunities to phase out other GHGs that are used in industrial processes, such as in computer chip manufacture. Therefore, some of the other GHGs could be eliminated long before 2050, whereas the economic pressure to continue to use fossil fuels for energy is enormous. However, this is not to argue that it isn't important to reduce other GHGs. As noted by the IPCC (2007), including non- CO_2 GHGs and land use CO_2 in mitigation policies would provide greater flexibility for stabilizing atmospheric GHGs and allow for a larger budget for $CO_{2.}$ For instance, reducing emissions of industrial non- CO_2 GHGs or agricultural methane and nitrous oxide would permit greater emissions of energy related $CO_{2.}$ These trade-offs could be particularly valuable for developing countries. For Europe, the largest potential benefits could come from increasing sinks, for instance by transforming marginal agricultural land into forests.

We give results for the 25% probability of global warming exceeding 2° C. For this, Meinshausen *et al's* data need to be revised to account for two factors. First, we do not consider CO_2 emissions from changes in land use (responsible for 18.1% of emissions between 2000 and 2005). After excluding the CO_2 budget for land use changes (assuming that this contribution stays stable), the allowable emissions from global energy CO_2 declines to 819 Gt. Second, between 2000 and 2010 the emissions from energy CO_2 were approximately 285 Gt, which must also be subtracted from the allowable CO_2 budget.[13] This leaves a budget of 534 Gt of CO_2 from energy sources between 2011 and 2050. This is approximately 13.35 Gt per year over the next 40 years, compared to current emissions from energy related sources of 29 Gt per year. This CO_2 budget is similar to other budgets (after adjusting for the starting year) calculated by other researchers.[14]

The possible emissions of energy related CO_2 after 2050 will depend in part on how much of the CO_2 budget is used up between 2010 and 2050 and the amount of CO_2 that is captured by sinks. In terms of per capita emissions, a level of around 33% of 1990 total emissions is considered sustainable (WBGU, 2009; Allen et al., 2009; UNSW Climate Change Research Centre, 2009). This is equivalent to approximately 7 Gt, or 1 tonne per person, given a 2010 global population of 6.85 billion. With population growth, the per capita emission allowance will decline.

How fast do CO_2 emissions need to decline to stay within the carbon budget and to reach a sustainable level of 7 Gt? This depends on the date when serious action to reduce CO_2 emissions begins. Before the date of serious action, we assume a BAU growth rate of 2% for *global* CO_2 emissions, which is less than the observed rate of a 3% increase per year between 2000 and 2006. We assume that current actions by China to improve the CO_2 intensity of their

[12] This is also partly due to data limitations. In addition to the estimate for an energy related CO_2 budget, Meinshausen et al. (2009) also provide an estimate for a total GHG budget for the fifty years between 2000 and 2050 of 1500 Gt CO_2 equivalent, i.e. including all Kyoto GHGs. However, as it is a very rough figure, based on an estimate that non-CO_2 gases would form approximately a third of all CO_2 equivalent gases.

[13] The last year for estimated emissions are for 2008 (EPA, 2010). We assume no increase in emissions for 2009 and 2010 due to the global recession. Energy emissions up to 2006 and emissions from land use changes are calculated by the authors using the CAIT data.

[14] In addition to Meinshausen et al., 2009; see Allen et al., 2009 and WBGU, 2009.

European Commission
Enterprise and Industry

economy will reduce the rate of emissions growth. After this date, we calculate the necessary annual rate in the decline of CO_2 emissions to prevent the remaining CO_2 budget from being exceeded.

Our results are summarized in Table 2.3 for five starting dates for emission reductions and are graphed in Figure 2.3. The results give the constant rate of decline in emissions for the longest possible time period for reducing CO_2 energy emissions while at the same time staying just within the remaining CO_2 emissions budget, which varies with the starting year for serious action. To give an idea of what could have happened if action to reduce GHGs had begun right after the Kyoto meeting of 1997, the first row of Table 2.3 gives an emission reduction path starting from 2000. In this case, a reduction of 1.84% per year in global CO_2 emissions would have allowed 61 years to reduce emissions to a sustainable level of 7 Gt without exceeding the cumulative carbon budget of 819 Gt. This is both a considerably lower rate and longer time period compared to all other starting years.

Table 2.3 Annual decline in global energy CO_2 emissions to reach sustainable emissions of 7 Gt per yr

Start year of action	Remaining energy CO_2 Budget (Gt)	Remaining years to reach sustainable emissions (7 Gt)	Minimum required annual decline in emissions
2000	819	61	1.84%
2012	504	32	4.30%
2015	410	25	5.60%
2020	244	14	10.30%
2025	61	3	34.50%
2030	-184	-	-

Data source: Energy related CO_2 emissions for 2000-2010 from the World Resources Institute (CAIT database, EIA reference case). Calculations by the authors.

The next row of Table 2.3 gives the results for starting serious action to reduce CO_2 energy emissions in 2012. In this case, the maximum time period for reducing emissions, at a constant rate of decline of 4.3%, is 32 years, with sustainable emission levels reached after 32 years in 2044. Using a slower rate of decline would exceed the remaining CO_2 budget, while a faster rate of decline would provide fewer years for reducing emissions. If action is delayed until 2020, only 14 years are left to reduce emissions to the sustainable level, requiring a high annual rate of decline of 10.3%. Once 2030 is reached it is too late – the remaining CO_2 budget has been exceeded by 184 Gt.

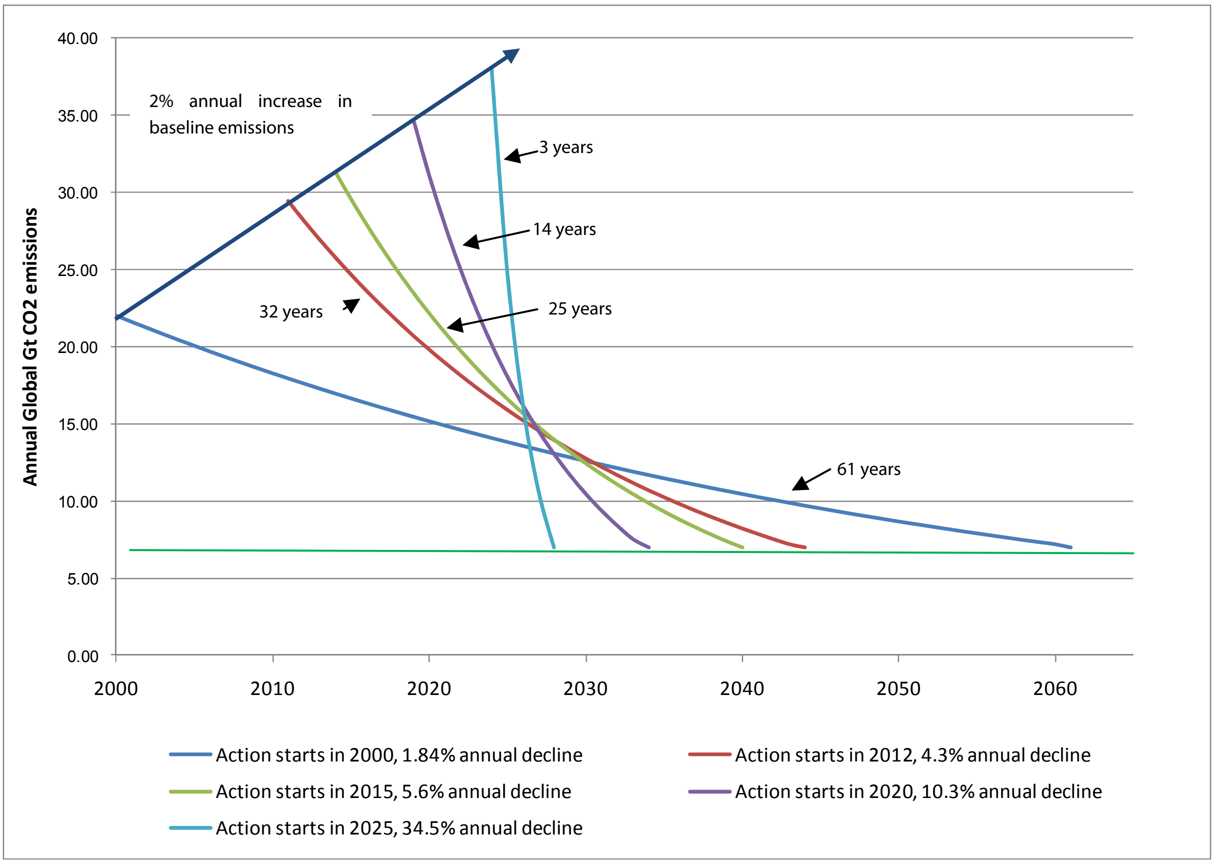

Figure 2.3 **Maximum global CO_2 emission paths by start year for effective action, using constant annual decline rates.** The arrows give the number of years remaining before emissions must drop to the sustainable level of 1 tonne per person (green line).

The results in Table 2.3 show that every year of delay in taking serious action to reduce energy CO_2 emissions substantially reduces flexibility for finding innovative solutions: the time left to reduce emissions shrinks and the rate at which emissions must decrease grows. The window of opportunity for serious action is therefore short and covers approximately one decade from 2010. Given current political will, action is highly unlikely in 2011, which is why the first example in Table 2.3 assumes that serious action begins in 2012.

2.3.5 Equity principle for CO_2 emission reductions

The necessary global rate of decline for CO_2 emissions, as shown in Table 2.3, includes high emission countries such as Canada, the United States and Australia, medium emission countries such as Sweden and France, and low emission countries such as Vietnam, Nigeria and Laos. For the EU-27, average per capita energy CO_2 emissions in 2006 were 8.4 t (metric tonnes), compared to 19.3 t in the United States.

There is currently no internationally accepted formula for CO_2 reduction rates per country, other than agreement in principle that very low emitters have a right to increase energy related CO_2 emissions as a part of increasing living standards, requiring high per capita emitters to take on more of the task of reducing emissions. Although 'common but differentiated responsibilities' are a key principle of the United Nations Framework Convention on Climate Change (UNFCCC), the Copenhagen Accord (which is not an official outcome of the 2009 negotiations) does not include such a principle (although 'equity' is mentioned), nor does it include a binding emission allocation system.

Several suggestions exist in the literature[15] for equitably allocating emissions up to 2050 and how to take account of historical emissions. Most of these methods have a per capita target for emissions, try to account for historical emissions or the right of developing nations to emit relatively more in the future than the developed nations, and many also take emissions trading into account to even out differences between allowances and actual emissions.

The simplest plausible outcome is agreement on a per capita equity share, where the per capita emissions 'quota' is identical for all countries.[16] Even if this simple equity principle is accepted, the date for fixing the population share must still be agreed upon. Options include using the current share of the world's population, an expected share in the mid-term future, or an expected share in 2050.[17]

The global population share of the EU-27 was 7.4% in 2008, but the expected share in 2050 is 5.4%, due to estimations of only a 1.6% increase in the population of the EU-27 compared to a 26% increase in the global population.[18] The EU will therefore benefit from fixing per capita CO_2 emissions to the current population share, although the United States will not.[19] However, a major advantage of using current shares is that it rewards countries for limiting population growth (the P in the IPAT equation). For simplicity, we assume that per capita CO_2 emissions will be set using current populations in 2008.

2.3.6 Energy CO_2 emission reductions for the EU-27

GHG emissions in the EU-27 have remained relatively stable in the past decade, with even a slight decline since 2004, as shown in Figure 2.4 for total GHG emissions and for energy related CO_2 emissions (with a decline of 1% per year since 2004). Recent preliminary estimates from the EEA indicate that EU emissions in 2009 could be almost 7% lower than in 2008, largely due to the economic recession,[20] but we assume that this will be short-lived, with a return to a trend of negative 1% per year

[15] See WBGU, 2009; Baer et al. 2008; Höhne and Moltmann, 2008; GCI, 2005; Meyer, 2000; Höhne et al., 2006; Spierre et al., 2010; Kanitkar et al., 2010; Singer, 2004; Jamieson, 2005.

[16] This was not adopted in the Kyoto Protocol, even for Annex I high emission countries. For example, Australia was permitted to increase emissions over 1990 levels by 8%.

[17] A second option for equity is to base emissions on historical records. For example, the United States, since 1900, over 300 Gt of CO_2. Using historical emissions, which would be favoured by China, would results in future emission shares for developed countries of close to zero, requiring all emission rights to be 'purchased' from developing countries.

[18] The estimated population of the EU-27 in 2050 is 503 million with immigration (EC, 2008), while the estimated global population is 9.3 billion in 2050, using the UN's middle population estimate, compared to almost 6.9 billion in 2010.

[19] The US population is expected to grow almost 36% from 308.9 million in July 2010 to an estimated 419.8 million in 2050 (US Census Bureau, http://www.census.gov/population/www/projections/usinterimproj/).

[20] EEA Report No. 7, 2010. Official 2009 figures will be published in May/June 2011.

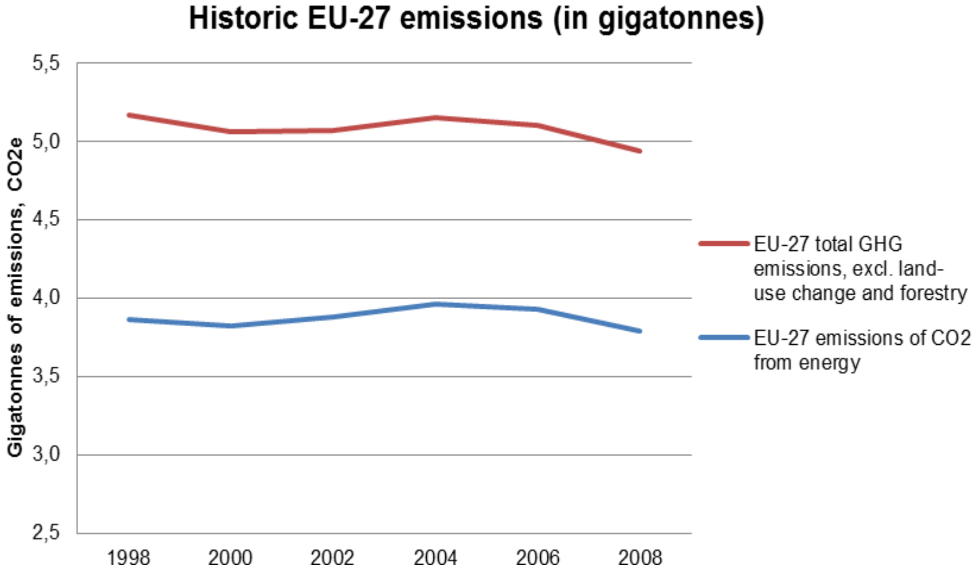

Figure 2.4 **Total GHG (in CO_2 equivalents) and energy related CO_2 emissions in the EU from 1998 to 2008.**

There are two methods, both based on a simple equity principle, for estimating the rate of decline in EU energy CO_2 emissions to 2050. The results are summarized in Table 2.4. The first method is to limit future EU-27 emissions to its equitable share of the remaining energy CO_2 budget of 530 Gt between 2011 and 2050. With a global population share of 7.4%, the equitable EU-27 budget is 39.2 Gt. At current energy CO_2 emission rates of 3.8 Gt per year, the EU-27 energy CO_2 budget would be consumed in a little over ten years. Using the same method as in Table 2.1 and a starting year of 2012, the EU-27 would need to reduce its emissions within 23 years (by 2034) at a rate of 8.4% per year in order to keep cumulative emissions approximately within 39.2 Gt.

Table 2.4 **EU-27 energy CO_2 emission reduction scenarios to reach a sustainable level of 1 tonne per capita (using 2008 population)**

Start year	Emission trading	Annual percent decline	Emission purchases (Gt)	Years to reach sustainable emissions
2012	No	8.4%	0.0	23
2012	Yes	5.0%	26.2	38
2015	No	12.7%	0.0	15
20% by 2020	Yes	1.5% to 2020, 6.1% after	38.5	38
30% by 2020	Yes	2.8% to 2020, 5.6% after	32.5	38

Data source: Energy related CO_2 emissions for 2000-2006 from the World Resources Institute (CAIT database, EIA reference case). Calculations by the authors.

The second method assumes emissions trading where the EU-27 can 'purchase' some of the unused emissions of poorer countries and delay reaching its sustainable level of emissions until 2050. Under this scenario, the EU-27 could reach its sustainable 2050 energy CO_2 emissions allowance if it started in 2012 and if emissions declined by 5.0% per year. However, compared to the first method, the EU-27 would consume 65.4 Gt of the global 530 Gt energy CO_2 budget. This would require the EU-27 to purchase emission permits for 26.2 Gt of CO_2.

The current EU policy is to reduce GHG emission by 20% below 1990 levels by 2020. There is also ongoing discussion to reduce the levels to 30% below 1990 emissions. Energy CO_2 emissions for the EU-27 were 4.077 Gt in 1990. A 20% and 30% reduction would require annual emissions in 2020 of 3.26 Gt and 2.85 Gt respectively. To meet the 20% goal, energy CO_2 emissions would need to fall by 1.5% per year. The 30% goal is more challenging, requiring a 2.8% decline in emissions. Both targets, although faster than the current trend rate of a decline of 1% per year, delay serious action on global warming until after 2020. So how much faster would emissions need to decline after 2020?

Without emissions trading, the 20% goal would use up 34.9 Gt of the carbon budget allowance for the EU-27 between 2011 and 2020, leaving only 4.3 Gt within the budget. The 30% goal would use up 32.4 Gt, leaving only 6.8 Gt. Neither provides a feasible option. With emissions trading, the annual rate of decline after 2020 to reach a sustainable 0.5 Gt of energy CO_2 emissions by 2050 is 6.1% for the 20% goal and 5.6% for the 30% goal. The amount of emission offsets that would need to be purchased are, respectively, 38.5 Gt and 32.5 Gt.

2.3.7 Energy CO_2 emission reductions for the United States

For comparison, we use the same methodology to calculate the necessary reductions in energy CO_2 emissions for the United States. With an estimated population of 310.5 million compared to a global population of 6.9 billion, the United States has 4.5% of the world population. Its remaining share of the global CO_2 energy budget of 530 Gt between 2011 and 2050 is therefore 23.9 Gt. At current rates of energy CO_2 emissions of 5.6 Gt per year, it would use up its budget in a little over 4 years. Its sustainable level of emissions for 2050, based on 2010 populations, is 0.31 Gt. Between 2005 and 2008 US energy related CO_2 emissions declined by approximately 1% per year. This rate is used for energy related CO_2 emissions before serious action to reduce emissions begins.

As expected, given per capita emissions in 2008 that are over twice the EU-27 average, the rate of decline in emissions for the United States is higher than the required rate of decline in Europe. As shown in Table 2.5, without emissions trading and a starting date of 2012, the United States would need to reduce its energy CO_2 emissions by 21.5% per year and reach its sustainable level of 0.3 Gt per year in 11 years (by 2023). This would be politically impossible. Using the alternative method of emissions trading, the United States would need to reduce its emissions by 7.1% a year and purchase 53.3 Gt of emission rights from other countries to reach a sustainable emissions level of 0.31 Gt in 2050. Delaying serious action until 2020 would require an annual decline in emissions of 8.5%, with emission purchases of 78.6 Gt.

Table 2.5 United States energy CO_2 emission reduction scenarios to reach a sustainable level of 1 tonne per capita (using 2008 population)

Start year	Emission trading	Annual percent decline	Emission purchases (Gt)	Years to reach sustainable emissions
2012	No	21.5%	0.0	12
2012	Yes	7.1%	53.3	38
2015	Yes	7.5%	63.7	38
2020	Yes	8.5%	78.6	38

Data source: Energy related CO_2 emissions for 2000-2006 from the World Resources Institute (CAIT database, EIA reference case). Calculations by the authors.

2.3.8 The feasibility of emissions trading

The ability of developed countries to purchase emission rights from developing countries reduces the annual rate at which energy CO_2 emissions would need to decline to prevent more than a 2 °C increase in the average global temperature. Emissions trading will be essential for the United States, since an annual decline of 21.5% per year, starting in 2012, would be politically and technically impossible. The EU-27 is better placed to manage a decline without emissions trading, with "only" an 8.4% annual decline required. However, this is extremely unlikely to be politically acceptable.

An analysis by WBGU (2009) uses a carbon budget approach and models the necessary rate of decline and the availability of emissions trading if low and middle emission countries increased their emissions over the short term. They find that emissions trading, if serious action to reduce emissions had begun in 2010, can reduce the annual decline in emissions for developed countries. In their model, the source of tradable emissions consists of countries with current per capita emissions of less than 2.7 tonnes. These countries currently account for 49% of the global population, emit 3.1 Gt per year, and have a remaining energy CO_2 budget from 2011 of 261 Gt. However, substantial technology transfer and financial assistance would be required to minimize additional CO_2 emissions in these countries. Furthermore, delay in taking serious action will reduce the amount of tradable emissions available.

Even with emissions trading, the required annual declines of 5% for the EU-27 and 7.1% for the United States will be challenging. Nor will emissions trading be a low cost solution. If we assume the most favourable plausible case of a 30% reduction for the EU below 1990 emissions up to 2020 and concerted action by the United States to reduce emissions from 2015, the United States and the EU-27 combined will need to purchase 96.2 Gt of emission permits. The remaining global energy CO_2 budget from the 'tradable' countries will be 248 Gt from 2015, assuming that emissions increase by 2% per year in these countries between 2011 and 2014 inclusive. The United States and the EU-27 will need to purchase 38.8% of the carbon budget of the tradable countries. Competition will be intense, since major economies such as China, Japan, and Russia will need to purchase emission rights themselves, plus the tradable countries will need to keep an increasing share of their carbon budget for their own needs.

China is likely to also be in the market for emission rights. Using the equity principle, China has a carbon budget from 2011 of 108 Gt, commensurate with its 20.2% share of the global population. Its 'sustainable' level of emissions is 1.3 Gt, but its estimated energy CO_2 emissions in 2010, based on a 2% annual increase since 2006, are 6.1 Gt, or approximately 4.7 tonnes per capita. If China begins serious action in 2012 to reduce its emissions to the sustainable level, it would need to reduce its emissions by 4.5% per year and reach sustainability in 2045. Even assuming that China begins to reduce emissions in 2012, which is unlikely, China will have no excess emissions to trade and is much more likely to be in the market to purchase emission rights.

2.3.9 Buying flexibility: increasing the energy CO_2 budget

The time available to decrease annual CO_2 emissions can be extended by increasing the size of the energy CO_2 emissions budget. This can be done by decreasing emissions from other GHGs, increasing sinks from land use changes, decreasing global CO_2 emissions from deforestation and other negative land use changes, reducing non CO_2 GHG from agriculture and industry, or actively removing CO_2 from the atmosphere.

In Europe, other GHGs contribute 0.851 Gt of CO_2e emissions, which equals 17.2% of all EU emissions in 2008. Some of these GHGs, such as methane from cattle, goats and sheep, will be difficult to reduce, unless diets changed to meat and milk sources that do not produce methane, such as reindeer. But other GHGs such as chemicals used in industry could be phased out, if research found substitutes. Land sinks in Europe remove 0.418 Gt each year of CO_2. Increasing forest cover could increase the removal of carbon, as long as forests or other lands were not used to produce biofuels. WBGU (2009) assumes optimistically that global land use changes could contribute only 50-60 Gt of CO_2 between 2010 and 2050, if action was taken to critically reduce deforestation in the developing world. Including this assumption would increase the global CO_2 budget to almost 600 Gt and the EU-27 budget to about 44 Gt.

The other alternative, which will be increasingly inevitable, is to actively remove CO_2 from the atmosphere. Biochar could be manufactured by burning organic matter in an oxygen free environment and then burying the charcoal that is produced. The most cost-effective method is to fund the production of biochar in developing countries. Pratt (2010) estimates that biochar could remove up to 1 Gt of CO_2 by 2030 in Asia. This would free up a little more CO_2 for energy use.

2.4 CO2 emissions by sector in Europe

CO_2 emissions are not concentrated in specific sectors, as shown in Figure 2.4, which gives the share of direct and indirect energy GHG emissions in Europe in 2008 for five main sectors: industry, transportation, commercial, residential, and other. These emissions are almost entirely due to CO_2. The direct emissions are due to fossil fuels burned in the sector, such as petrol burned in the transportation sector. The indirect emissions are from assigning power plant emissions to the sector of use. In the transportation sector, 4% of emissions are indirect, such as the use of thermal electricity to drive electric trains.

The major sources of energy emissions in Europe are industry and transportation (each accounting for 28% of total energy emissions), followed by the residential sector, at 24%. Most of the direct emissions from transportation, residential and commercial uses (accounting for 42% of European emissions) are not covered by the Emissions Trading Scheme (ETS). Clearly, actions to reduce demand for these forms of energy could have a significant effect on European CO_2 emissions. Figure 2.5 also highlights the importance of reducing transportation emissions in Europe.

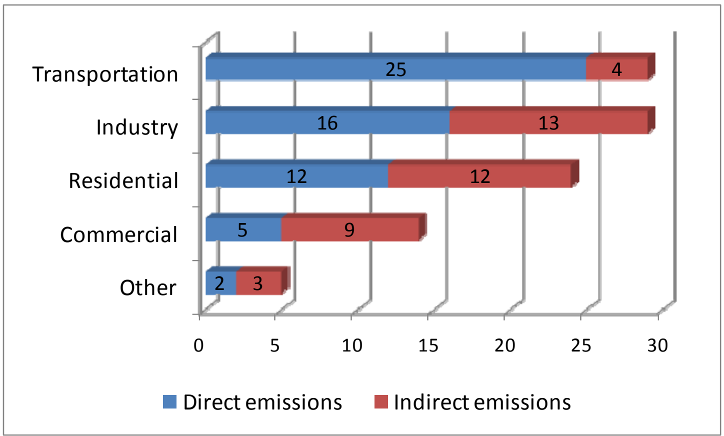

Figure 2.5 **Allocation of energy-related Greenhouse Gas Emissions by end use in 2008**
Source: European Environment Agency, 2010.

Furthermore, many emissions are due to households, such as residential emissions (24% of the total) and a significant share of transportation emissions. One estimate from 2001 is that household food, shelter, and transport uses account for 73% of all GHG emissions, although this is a global estimate, instead of an estimate limited to Europe (UNEP, 2010). The EEA (2010) has estimated the change in final energy demand in Europe by sector between 2007 and 2008 and reports that energy use by households increased, in contrast to a decline in energy consumption by many industries, agriculture, and transport.

These results show that serious actions to reduce GHG emissions need to target all sectors, including household energy use. It will not be possible to reduce GHG emissions by 80% to 85% by concentrating on industrial users and the energy sector only. Substantial reductions in energy use are also required for space heating and other household uses.

2.5 Conclusions

If serious actions to reduce energy CO_2 emissions had been implemented in 2000, the R&D investment model might have had time to play a substantial role in reducing emissions. At this time serious actions are unlikely to be implemented before 2012, and possibly not until 2015 or 2020. In all scenarios, there is not enough time to rely on the R&D investment model alone, due to lead-times of 10 to 15 years (until 2020 or 2025) to develop cost-competitive low or zero carbon alternatives to fossil fuel energy sources. Delaying global action until 2020 would leave only 14 years to reduce energy CO_2 emissions to a sustainable level and require annual decreases in emissions of 10.3%. Delaying until 2025 would leave only 3 years and require annual declines in emissions of 34.5%.

The available time is even shorter for the European Union, due to higher energy CO_2 emissions than the world average. With no emissions trading and serious action starting in 2015, EU emissions would need to fall by 12.7% per year and reach sustainable levels in 15 years.

A modification to current EU policy of a short term goal to 2020 and a longer term goal to 2050 creates some room for the R&D investment model, but only if it is possible to purchase emissions from other countries. This will be expensive, with possible costs estimated to increase over time from 100 USD per tonne in 2020, increasing to

600 USD per tonne in 2050. At an average price of 350 dollars per tonne, the cost of purchasing 38.5 Gt of emission permits would be approximately 450 billion USD per year, or roughly 3% of European GDP (in current dollars).

Even with the ability to purchase emission permits or increase carbon sinks, Europe is facing the need for a rapid decline in carbon emissions, although not nearly as great as the decline required in the United States, Canada, and Australia, where carbon emissions are double that of Europe. A decline in carbon emissions will require rapid technological innovation to increase the efficiency with which energy is used and to replace almost all current energy production with zero carbon energy. A significant decline is also needed in all major emitting sectors of the EU economy: transport, industry, residential buildings, and commercial buildings. For all of these reasons, the EU needs to introduce an *integrated* set of policies to address global warming that affects technical, social, behavioural and organisational innovation across all EU countries. The policies will need to include everything from a realistically demanding level of carbon taxes to changes in regulations on buildings design, freight handling, urban design, investment in public transit, and a *substantial* increase in public and private sector investment in R&D.

3 REVIEW OF PROPOSALS TO ADDRESS THE CLIMATE CRISIS

3.1 Introduction

This chapter examines the results of 16 studies that have examined how to reduce GHG emissions and thereby prevent dangerous climate change. The studies either develop technical scenarios for how emissions can be reduced or fictional scenarios that include actor dynamics in the face of plausible future events. This section also draws upon some of the climate change policy literature. Although the focus is on climate change mitigation (preventing dangerous climate change), we also briefly explore proposals to adapt to climate change. The focus of this review is, firstly, on the general format of the scenarios, and secondly, on the discussion of relevant issues related to different technologies and policies, both in the scenarios and in related literature.

Appendix A at the end of this report presents a more detailed overview of the scenarios, while Table 3.4 in this chapter provides a brief summary.

3.2 Methodologies, targets and timing in mitigation scenarios

About half of the scenarios in Appendix A and Table 3.4 extend to the year 2050, with the others looking at a shorter horizon somewhere around 2030. This has a significant effect on the policy advice mostly only for those scenarios that include a more detailed roadmap. However, there are other methodological differences in how the scenarios have been built. One scenario is using explicit back-casting based on cost minimization (IEA, 2010a), and about half of the scenarios are using long-term targets in either emission reductions or the use of specific low carbon energy technologies. The remaining scenarios have no specific targets, but focus on somewhat different issues each: the effect of carbon pricing or R&D support on emissions (Lazarus and Kartha, 2009); GHG abatement costs and the effect of carbon pricing on emissions (McKinsey, 2009); decoupling economy from energy and resource use (Giljum and Polzin, 2009); the effect of low/no GDP growth on the economy (Victor, 2008); meeting future demand for energy (Shell, 2010), the effect of globalisation on the world economy (World Bank, 2007), and the effect of various political, security-related or environmental world events on economies and society (National Intelligence Council, 2008)

Detailed roadmaps are included in several scenarios, which either focus on specific technologies (IEA roadmaps): concentrating solar power (CSP), photovoltaics (PV), wind power, carbon capture and sequestration (CCS), electric and hybrid vehicles, cement industry, or increasing the use of renewable energy sources to cover 100% of European electricity by 2050 (PriceWaterhouseCoopers, 2010).

General emission reduction targets and projected emission pathways (in the scenarios without specific targets but some indication) vary from 'no drastic cuts' by 2025, to 40% by 2050 to 80-90% reduction by 2050 from 1990 GHG emissions. This higher end is the currently understood necessary level at which the global average temperature increase may be able to stay within 2˚C, and the scenarios reaching this policy target are Worldwatch Institute and the Fletcher School (2009), McKinsey (2009), Netherlands Environmental Assessment Agency and Stockholm Resilience Centre (2009), Lazarus and Kartha (2009), European Climate Foundation (2010) and PriceWaterhouse-Coopers (2010). Some of these (especially European Climate Foundation and PriceWaterhouseCoopers) are very detailed, with others being more general.

Finally, although most of the scenarios do not give detailed timelines for their policy suggestions, they do consider immediate policy action or setting near-term targets for 2015 or 2020 to be necessary. Exceptions to this are Shell (2010) and National Intelligence Council (2008), which consider near-term targets (or tough longer term targets) either too challenging or too damaging for economies. Both of these scenarios are also written in a style which puts a strong emphasis on real life dynamics with conflicting views of multiple actors. For the authors of these reports, such conflicts seem to make strong (near term or future) policy action impossible.

3.3 Main topics in mitigation scenarios and related literature

Most of the studies focus on a low-carbon energy future, but, as mentioned above, some of them are limited to a specific type of energy (electricity) or look at a specific technology. The level of decline varies by scenario, with several limited to a 50% decline in CO_2 emissions by 2050, while others are more ambitious. The studies generally agree on several issues, such as the need for a combination of short-term actions and long-term planning, the crucial role of technology, and the large scale and scope of necessary change, especially in terms of the energy and transport sectors, with many studies referring to a 'transformation'. Although most studies also consider a carbon price system of some kind or another necessary, together with emission reduction goals, there is also some disagreement on the need for immediate emission reduction targets.

The main points of disagreement concern *how* to achieve reduced GHG concentrations. There are disagreements over the role of technologies, i.e. the types of innovations that are required (incremental vs. radical innovation, and the use of specific technologies) and in the required policies (the role of R&D, carbon pricing, energy efficiency and the role of behavioural changes). Several of these issues are discussed below.

3.3.1 Technologies

The literature generally argues for the necessity of disruptive and radical changes in how we meet our energy needs. However, the current system mainly supports incremental changes (Smith, 2009). Looking at the issue from the practical solutions' point of view, several studies promote the need for a Europe-wide super electricity grid (see Netherlands NEAA, 2009, or PriceWaterhouseCoopers, 2010), while others would prefer to see a system based on decentralized power production (see e.g. Girardet and Mendonca, 2009; or Hargroves and Smith, 2005). In each case, the study seeks to decarbonize the European energy sector by using renewable energy sources to a large extent.

Apart from the issue of the necessary infrastructural changes, many argue that energy technologies that already exist today (in commercial or near commercial form) can already deliver more than 50% of the necessary emission cuts (e.g. IEA, 2009; World Business Council for Sustainable Development, 2009), while others argue for a focus on fundamentally new innovations (Galiana and Green, 2009; Copenhagen Consensus Center, 2009).[21] Most however, agree that both incremental changes to existing technologies (such as efficiency improvements) and new technologies are necessary. The challenges of a transition away from a fossil fuel based energy system are acknowledged by many, with the pace of change slowed down by long development times for new general purpose technologies and the obdurate and stable nature of incumbent technologies. However, Smith (2009) argues that a much stronger coordinated effort must be made in order to get out of the lock-in situation that extends across not only economic sectors, but across current knowledge, education, engineering practices (including individual practices and social norms), infrastructure, public procurement and regulatory frameworks, all of which are parts of a technological regime - currently the hydrocarbon regime. Challenge-led policy making would seem the desirable option, and one that can possible lead to quicker change as well.

There is a considerable amount of disagreement in the literature on which specific technologies – already in commercial use or in development - would deliver results in the fastest, most efficient and inexpensive manner. Some studies (National Intelligence Council, 2008; Shell, 2010), see only a small **role for renewable energy sources** in the next 20-30 years, while others believe that a full-scale European-wide electricity system can be wholly based on renewable sources by 2050 (e.g. PriceWaterhouseCoopers, 2010).[22] Ignoring economic and social factors, the supply of renewables such as wind, solar, geothermal, and bioenergy appear to be sufficient to meet European demand (see Ecofys, 2009a; Ecofys, 2009b; EEA, 2006 and EEA, 2009). The Worldwatch Institute and the Fletcher School

[21] Hargroves and Smith (2005) also point out that whole system design often costs less than a sum of incremental changes in the same system.

[22] However, in the system suggested by PriceWaterhouseCoopers (2010), a significant proportion of the EU electricity supply originates in North Africa, in a combined EU-NA grid.

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Enterprise and Industry

(2009) also note that the renewable share (excluding large hydro) of *additional* global power production jumped from 5% to 23% between 2003 and 2008, so rapid advances have already been made in recent years. The most difficult constraints for a fully 'renewable' Europe are possibly due to the cost of building the necessary infrastructure and transition costs for such a technological regime change (Smith, 2009).

Many of the issues with making a transition to alternative technologies and systems are explored in greater depth in Chapter 7, where we examine the many policy constraints and the need for policy to be concerned with a portfolio of options, lead times, institutional barriers to new technologies and continual policy adjustments. Chapter 5 examines energy security as an important issue for climate change policy and resource scarcity – issues given poor attention in the scenarios (the Shell scenario being an exception). In terms of technological and infrastructural changes, one major challenge is ensuring system stability with increasing shares of intermittent renewables. Transnational grids and the use of a mix of different types of renewables can help achieve system stability (see Chapter 5).

Part of the dispute over specific technologies could be due to differences in timeframes (whether or not the study is looking at GHG reduction up to 2030 or 2050), to different conceptions of the rate of transition from one type of technology to another, or to different economic interests (an interest in supporting fossil fuel producers or in advancing renewables).

There are other currently existing, but developing technologies, on which there is disagreement, in terms of whether they should be policy priorities or not. **Nuclear power** is perhaps the most obvious one of them, with proponents (e.g. Lorentsen from the OECD (in OECD, 2008a); Stern, 2007; Galiana and Green, 2009; and Sachs, 2008) arguing for investment in advanced third and fourth generation nuclear power plants delivering safer low-carbon energy, and opponents (e.g. Girardet and Mendonca, 2009). Many reports simply leave nuclear energy out from the discussion, arguing that nuclear power should not be considered part of the solution due to problems related to costs, time (too slow), waste, proliferation, fuel supplies (dependent on unsustainable uranium mining from foreign sources), security and safety. [23]

Biofuels is a second contentious topic, although second and especially third generation biofuels are more promising. Girardet and Mendonca (2009) note that the concept of carbon negativity - removing more carbon from the atmosphere than releasing into it – should become part of a definition of a biofuel. Efficiency of this type of fuel is still a problem, however, as currently biofuels are much less efficient for running vehicles than, for example, photovoltaic power (see Girardet and Mendonca, 2009: 220). There is little disagreement in the literature that transport fuels need not only strong improvements in efficiency, but a total overhaul, but whether the answer lies within biofuels or within electric or hydrogen fuel cells, or a combination of these is not yet clear.[24] The changes in liquid transport fuels affect infrastructure somewhat less than a transformation in other energy supply forms. But considering the three-fold projected growth in transport by 2050 (IEA, 2008) many also consider encouraging behavioural shifts that reduce the need for transportation.

A third contested method is carbon capture and storage, **CCS**, where carbon is captured directly prior or immediately after combustion, and stored in geological formations or in the deep ocean. CCS is considered by many to be an essential part of climate change mitigation (World Business Council for Sustainable Development, 2009; World Economic Forum, 2009; Lorents Lorentsen from the OECD (in OECD, 2008a); IEA, 2008 and 2010a; Stern, 2007; Galiana and Green, 2009; National Intelligence Council, 2008; ECF, 2010, and Sachs, 2008), with some considering it only as a transitional technology on the way to decarbonizing the economy, and others as a more permanent option.[25] However, Girardet and Mendonca (2009) warn that CCS is not a practical solution for most existing power sta-

[23] Safety concerns due to the effect of the March 2011 Japanese earthquake on the Fukushima Daiichi nuclear plant could strengthen the arguments of the opponents, at least in respect to regions with a high earthquake risk.

[24] Hydrogen fuel cells are of course also being developed for more general energy storage, see e.g. Hargroves and Smith (2005) or Sachs (2008).

[25] However, until the issue of potential leakage is resolved, it cannot be a permanent solution. See discussion of risks of CCS, e.g. in Stephens and van der Zwaan, (2005), Wilson et al. (2007), and Klass and Wilson (2009). CCS operates at a significant energy penalty (IEA, 2010a, p. 121). Extra

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tions, and furthermore, it will not take existing CO_2 from the atmosphere. Instead, they suggest that biosequestration – absorption of atmospheric CO_2 by soils, forests and aquatic vegetation – would be a considerably better way. Land and ocean carbon sinks currently absorb more than 50% of the CO_2 emitted by human societies. Climate change can reduce this amount, but efficient action can turn the reduction into an increase, with related positive effects, e.g. on biodiversity. There is also a technological solution to capturing CO_2 directly from the air through chemical processes, and although this technology is still in its infancy, Sachs (2008) sees great potential in it.

A third contentious issue is **geo-engineering,** deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming (Royal Society, 2009). Geo-engineering is often limited to methods to directly affect the earth's climate system through the use of technologies that reflect solar radiation from the sun back into space, although the Royal Society report also includes Carbon Dioxide Removal (CDR), such as land use changes that act as carbon sinks (these are discussed in Chapter 2). Figure 3.1 compares the cost and effectiveness of several geo-engineering methods (space reflectors, ocean fertilization, and stratospheric aerosols) against CDR methods such as biochar production. To date, the most cost effective method is estimated to be adding reflective aerosols to the stratosphere.

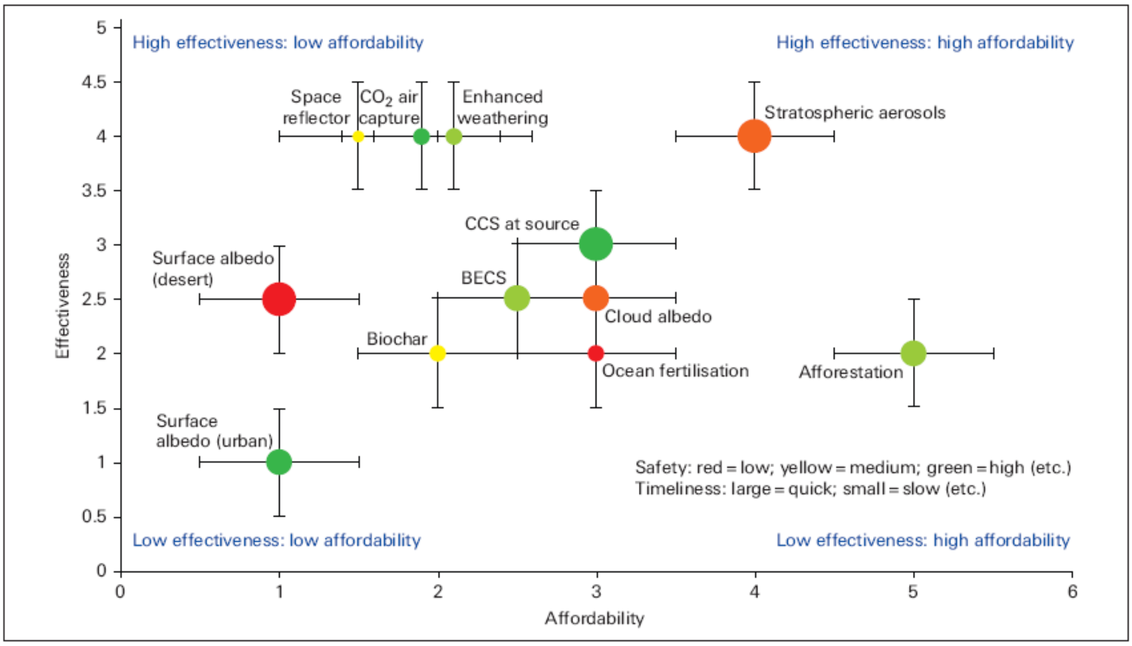

Figure 3.1 **Effectiveness and affordability of different geo-engineering options,**
Source: Royal Society (2009, p. 49)

Geo-engineering is not discussed in the scenarios reviewed in this chapter, largely because there are significant risks and the technology is untested. The Royal Society (2009) report concludes that there is room for geo-engineering as a strategy to complement mitigation and adaptation measures, although the experts find that CDR methods are preferable to geoengineering through Solar Radiation Management methods (SRM). This is because the former "effectively return the climate system closer to its natural state, and so involve fewer uncertainties and risks" (Royal Commission, 2009). However, CDR methods are slow-acting and relatively expensive and therefore may be unable to prevent dangerous climate change. SRM methods can act quickly and for this reason "may serve as a useful

power capacity is needed to compensate for the energy efficiency loss. Worldwide, 26 billion USD have been committed to the demonstration projects for CCS (IEA, 2010, p. 121).

backup in the future if their risks prove to be manageable and acceptable, and mitigation action proves to be inadequate, or if it is believed that a tipping point of the climate system is approaching" (Royal Society, 2009, p. 50).

SRM could help to avoid certain climate related impacts, but it cannot prevent all of them. Since they do nothing to reduce atmospheric CO_2 concentrations, they would not prevent an increase in ocean acidification with possibly disastrous effects on marine ecosystems from a loss of coral reefs, molluscs, and other marine life that are unlikely to survive a rapid decrease in pH levels (Flannery, 2005). Furthermore, the termination of geo-engineering methods could result in severe, rapid global warming from increasing CO_2 levels. Their use would need to be linked to intensive efforts to remove atmospheric CO_2 to prevent such rebound effects.

SRM is not an official strategy of any government. Advocacy for SRM can be expected to rise if the costs of climate change effects such as storm damage, migration of diseases, droughts and flooding increases substantially.

3.3.2 Policies

Public financing of R&D for new low-carbon energy technologies gets extensive support from the literature. Specifically, for example, IEA (2010a), OECD (2008b), Stern (2007) and Galiana and Green (2009) see a crucial role in much higher public R&D expenditure, up to 10 times current (relatively low) levels. Galiana and Green argue that if sufficient R&D investments are made immediately, necessary carbon emission reductions will follow without nations having to commit to near term cuts in emissions. In their vision, the R&D funds must be separated from political interference. This optimistic view is contradicted by the data presented in Chapter 2, which shows that there is insufficient time to rely on the 'R&D solution' alone. Smith (2009) notes that innovation research shows that most innovation does not stem from R&D and that the current focus on increasing R&D for energy technologies is misplaced. R&D by firms most commonly delivers incremental innovations, i.e. it works as a problem-solver during an innovation process, but simply pouring money in will not deliver revolutionary technologies. The governmental (or intergovernmental, as Smith argues) focus should be less for pure R&D support, and more for improved system design, where the system is the new technological regime to be developed.

The reviewed studies mostly agree that a **carbon price system** is a necessary part of climate change policy. Victor (2008) concluded from his scenario studies for the Canadian economy that a carbon price has the greatest effect in reducing GHG emissions, delivering up to a 30% reduction in emissions by 2035 compared to 2005 levels.

Most of the studies examined in this chapter do not delve into the optimum method for pricing carbon, i.e. whether it should be through a cap-and-trade system or a direct carbon tax, or both. However, there are arguments about the size, universality and impacts of carbon pricing. For example, Galiana and Green (2009) argue that a carbon price should be initially low (e.g. around US$5 per tonne of emitted CO_2), rising over time (e.g. doubling every 10 years), and this would eventually finance the R&D for new low carbon technology, as long as governments commit to the R&D. Similarly, the Worldwatch Institute, the Fletcher School (2009) and the IEA (2010d) believe that carbon prices should increase over time.

Against these views, PriceWaterhouseCoopers (2010) argues that the carbon price should start high enough as well as stable enough to encourage sufficient investment in renewables and discourage fossil fuel use. Many (e.g. Stern, 2007; Fankhauser et al., 2008; Sorrell, 2010) take the view that a carbon price can induce innovation in energy efficiency, and e.g. Popp (2002) provides some evidence of this. Carbon pricing may also offset problems with the rebound effect[26] (see e.g. Giljum and Polzin, 2009), and therefore have a two-way impact on energy efficiency. This

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[26] Rebound effect refers to behaviour change after certain efficiency gains, e.g. leaving lights on longer with more efficient energy lamps, or increasing room winter temperature when heating costs less. The evidence is that direct rebound effects are usually fairly small. For household heating, household cooling and personal automotive transport in developed countries, the direct rebound effect is likely to be less than 30% and probably closer to 10% for transport (Sorrel, 2007, p. vi). However where energy efficiency significantly decreases the cost of production of energy intensive goods, rebounds may be larger. Direct rebound effects may be expected to be larger in developing countries where demand for energy services is far from saturated. This is supported by the limited empirical evidence available. In some cases, the direct rebound effect may exceed unity (Sorrell, 2007, p. vii).

is also suggested by Sorrell (2010). As regards the universality of carbon markets, the OECD (2008b) argues that a unified global system is necessary, whereas PriceWaterhouseCoopers (2010) believes that regional systems (e.g. EU-wide) can also work, inducing change – for example, through lowering costs of technology – at the global level. The OECD (2008b) believes, however, that carbon prices will not be sufficient to overcome micro-level non-market barriers, such as the split-incentive,[27] and so standards and regulatory codes will also be necessary. David Foster from the Blue Green Alliance (in OECD, 2008a) notes that to avoid global speculation on carbon prices, an auction-based allocation system should be set up within an emissions trading system.

There are also some rather critical views on carbon pricing. Galiana and Green (2009) would not prioritize a carbon price system over governmental R&D commitments, believing that markets would not deliver the necessary basic R&D and governments would lack credibility regarding longer term price signals (due to changes in governments). Similarly, Adler (2010) argues that political parties will never set carbon prices high enough to spur sufficient investment in innovation. Finally, the Copenhagen Consensus Center (2009) put together an expert panel of five economists (three of which are Nobel laureates), and the panel were of the opinion that carbon pricing would be the least useful near-term policy option.[28]

There is agreement in the literature on the benefits of **efficiency measures** to significantly decrease energy and material inputs, thereby both lowering costs and reducing climate impacts, as long as efficiency measures are combined with measures to prevent **rebound effects**. Some promote efficiency measures as the key climate change policy, arguing that it can lead to significant savings in, for example, end-use efficiency - delivering up to 50% of necessary annual emission reductions (OECD, 2008b), or even up to 75% (Lovins, 2004). Victor (2008), however, quotes Haberl et al. (2006) in noting that, up until now, efficiency increases have fuelled more GDP growth than they have reduced resource consumption. Others (World Business Council for Sustainable Development, 2008; Girardet and Mendonca, 2009; Stern, 2007; Giljum & Polzin, 2009 and Sorrell, 2010) are also critical of the benefits of a strong emphasis on efficiency without coupling this with necessary behavioural changes, in particular on the end-user side, to prevent rebound effects. This would occur if the savings from lower electricity prices from the use of energy efficient are spent on more appliances. There are estimates that efficiency increases can even increase the total energy or resource consumption (the so-called backfire effect, see Sorrell, 2010). Sorrell also warns that measures to improve energy efficiency can themselves often consume more energy than what is generally assumed. However, the authors of the IEA (2010a) Blue Map scenario believe that efficiency savings should generally win over rebound effects. Some of the other reviewed scenarios also mention the rebound effect, but few offer solutions. As exceptions, IEA (2010d) and Giljum and Polzin (2009) support coupling efficiency improvements with behavioural change by keeping energy and material costs to end-users the same (as before efficiency gains) through e.g. taxes.[29]

Behavioural change is considered important in many of the scenarios, but few discuss the issue in depth, or offer solutions. Specific solutions are, however, discussed e.g. by McKinsey (2009) and NEAA (2009), with both focussing on end-user opportunities for change. McKinsey brings up examples of reduced travel, or a modal shift in travel, and reduced consumption of energy and meat,[30,31] while NEAA note that changing consumption patterns is crucial, but raising awareness is not sufficient. Raising awareness regarding the urgency of necessary changes, however, may help with acceptance of government measures, such as taxes on fuel carbon content. EU also has many opportunities in setting product standards, or banning or discouraging products harmful to the climate. Further, IEA

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[27] Split-incentive refers to the problem that, for example, the owners of a property do not have the incentive to pay for energy efficiency related refurbishment, when it is the tenants that get the benefit of lower energy bills.

[28] Climate engineering and other technology-led policy responses were their top choices.

[29] Also, a material input tax would help in both increasing metal recycling and higher resource efficiency in the use of industrial and construction minerals (Giljum and Polzin, 2009).

[30] McKinsey do not include behavioural change in their abatement levers, as such change is difficult to influence and therefore also difficult to quantify in advance.

[31] The concept of sufficiency (of consumption) is supported, for example, by Sorrell (2010) and Girardet and Mendonca (2009).

(2010d), together with much of the literature, support removing fossil fuel subsidies,[32] and note that this would also be likely to change behaviour, i.e. reduce demand for energy in the long run. In its last World Energy Outlook the IEA estimates that a universal phase-out of all fossil fuel consumption subsidies by 2020 will cut global primary energy demand by 5% (IEA, 2010d, p. 14).[33] WBCSD (2010) emphasize the role of research into general behavioural motivations and triggers for behavioral change,[34] while also focussing on the role of changes in business structures and culture, new business models, more interaction between customers and businesses (users and producers). Further **organisational issues** are discussed in some of the scenarios, with e.g. Shell (2010), WBCSD (2010) and the National Intelligence Council (2008) all considering new partnerships between businesses, civil sector, public sector and academic organisations important in tackling many of the challenges around energy and material use. WBCSD also points out the importance of social innovation, for example, to create new business models, new customer behaviour and new ways of interacting between providers and users. However, most of the scenarios do not focus on organisational issues.

Cultural change necessary to achieve climate change policy goals is barely discussed in the scenarios, or other reviewed literature. Hargroves and Smith (2005) are an exception in that they emphasize cultural change towards considering energy waste as unacceptable a key issue. Another view is given by Worldwatch Institute and the Fletcher School (2009), who suggest that rapid changes may sometimes take place without necessary cultural adjustments, giving an example of Africa's "telecom leapfrogging", i.e. the widespread adoption of mobile phones. They suggest that for Africa, "the future will essentially depend upon the availability and affordability of modern renewable energy along with the infrastructure that delivers it to end-users" (p. 38). If true, this of course would also be relevant for Europe, for example.

3.3.3 Real life actor dynamics

The energy roadmaps and scenarios for a low-carbon future focus largely on technically plausible futures and their likely costs and benefits, using assumptions about learning curves and economic rationality on the part of actors. Despite useful insights, such work does not illuminate how technological changes arise through the dynamic interactions between a range of actors with different perspectives and goals (Foxon et al., 2010, p. 1204). With some exceptions, actor dynamics are missing from the scenarios. Some studies pay attention to the constraints for policy but there is only limited discussion of the strategic games between business and political actors, the link between energy security and climate policy, changes in ideology and beliefs about the proper role for government in dealing with market failures. They hardly address the important issue of what the public will want and expect from policy and business.

An alternative method is to develop fictional scenarios that explore the possible interactions between different actors and the effect of plausible events on outcomes. An example is the two scenarios developed by Shell (2008). It explores changing policy priorities, international economic relations and the role of local authorities and civil societies in the face of three assumptions for future energy supply and demand:

1. *A step change in energy demand*, due to China and India entering their most energy-intensive phase of economic growth.
2. *Supply will struggle to keep pace*: by 2015, the increase in production of easily accessible oil and gas will not match the projected rate of demand growth; alternative sources of supply will have to be relied upon. This will increase the importance of energy security in many countries.

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[32] Others supporting the removal of fossil fuel subsidies include Worldwatch Institute and the Fletcher School (2009), Lazarusand Kartha (2009), IEA (2010b), World Future Council (2009) and Stern (2007).

[33] In 2009, fossil-fuel consumptions subsidies amounted to $312 billion (IEA, 2010d, p. 13). The annual level fluctuates with energy prices, domestic pricing and demand. In 2008 subsidies were $558 billion (ibid, p. 13).

[34] Research on sustainable consumption deals with these issues. See e.g. OECD reports on this topic: http://www.oecd.org/department-/0,3355,en_2649_34331_1_1_1_1_1,00.html.

3. *Environmental stresses are increasing,* meeting with opposition from environmental groups.

Shell develops two scenarios, Scramble and Blueprints, each of which is briefly described below.

In the **Scramble** scenario national actions to reduce CO_2 emission are sacrificed in a search for energy security. Countries continue to use fossil fuels and increase coal consumption due to an increase in the cost of other fossil fuel sources such as natural gas or oil. Without a long-term coherent policy, countries and firms do little more than react to changing conditions, without consideration for the longer term impacts. For instance, rising costs due to a fall in the supply of petroleum compels greater investment in coal – the worst fossil fuel in terms of CO_2 emissions. The scenario assumes that governments react to supply crises through drastic increases in energy prices to constrain demand, resulting in economic damage and political unrest. This finally forces governments to collaborate on an international agreement over energy security and climate change, but 20 years have been wasted. In addition, some of the actions to reduce demand conflicts with long-term goals to address climate change. For instance, strict energy efficiency standards prevent investment in alternative energy technologies.

Actor dynamics play a large role in this scenario. National governments compete with each other for favourable terms of supply or for access by their energy companies. There is no international climate agreement because of the focus on energy security. Growing CO_2 emissions result in climatic changes that provoke environmental protests over the construction of coal electrical plants and over environmental degradation.

The **Blueprints** scenario provides a more optimistic scenario. It describes a world where concerns about energy supply, demand and climate stresses forge new alliances that promote action in both developed and developing nations. The drivers for change begin at the level of cities or regions. These are supported by industry demands for a stable regulatory environment. In 2012, several nations agree to an emission trading scheme (ETS) for carbon. China and India sign up to climate agreements in return for technology transfer and investment. These are funded through a proportion of the funds raised from the ETS. The ETS and a carbon price drive an increase in efficiency measures, CCS, clean technology, and a mass-market for electric vehicles. The growth in the use of electric vehicles reduces demand for oil and possible price shocks from a gradual fall in oil supply.

In both scenarios, fossil fuels account for around 60% of primary energy use but overall energy and fossil fuel consumption is lower in the Blueprints scenario.[35] No estimates are provided about GHG emissions.

Evaluation of scenarios containing actor dynamics

The fictional scenarios by Shell (2010) and the National Intelligence Council (2008) incorporate real life dynamics with multiple actors and conflicting interests.[36] They usefully bring out differences in national interests, the issue of energy security as an important issue for government and society, and the role of civil society. These aspects are often ignored in economic models, which are consequently over-optimistic about government climate policy.

Fictional scenarios also have their limitations. It is not possible to envision all possible future events or shocks to the system or the actions that are likely to be taken by different actors. Due to the biases of the authors, some issues may not be addressed at all.

An evaluation of actor dynamics can also be incorporated into scenarios that examine what needs to be done to reach certain goals, such as preventing more than a 2 degree rise in the average global temperature as in the WSCSD (2010) report. Although the report generally concentrates on relatively smooth cooperation between actors, it also includes a brief analysis of various risks from conflicting interests or other developments. Further, it discusses a number of enablers for change within the reach of various societal actors, and emphasizes the role of cities, together with Worldwatch Institute and the Fletcher School (2009) and Shell (2010). PriceWaterhouseCoopers (2010) discuss, in connection with their goal of 100% renewable European electricity, a number of illuminating case studies of earlier instances of large projects where political and industrial will have been aligned, various risks handled suc-

[35] In Scramble fossil fuel consumption is 512 Ej in 2050 (58.2% of total primary energy), in blueprints it is 487 Ej (63.2%).

[36] Fictional scenarios are widely used in many different areas where future uncertainty can affect the actions taken by governments and firms. Other relevant examples include several scenarios developed by the OECD on the future of biofuels (OECD, 2009).

cessfully and the project goals achieved.[37] Most of the reviewed literature, however, does not pay much attention to actor dynamics, although, conflicts of interests are mentioned as barriers to be overcome (see more about barriers in a further section in this chapter).

3.3.4 The viability of continuous economic growth

Most of the literature talks about tackling climate change while ensuring economic growth, and takes economic growth as granted for a successfully transformed world, although preferably, in this view, economic growth would be sufficiently decoupled from energy and resource use. In contrast, some of the research on climate change controversially assumes that the assumption of continuous economic growth is part of the problem. This section provides a very brief overview of this line of research.

With some notable exceptions, there is agreement that economic growth based on resource use cannot grow forever, given a finite supply of physical resources. However, there is little agreement on how long economic growth can continue (will the world be able to sustain a population of 9 billion if everyone consumes at the rate of current billionaires?) or if input substitution and recycling can continually solve the problem of finite resources. Alternatively, virtual consumption could increasingly replace real consumption, permitting the appearance of continuous economic growth. Regardless of the answers to these questions, some research assumes that an effective solution to climate change will require an end to expectations of continuous resource use in developed countries and its replacement by an emphasis on the quality of life.

Beddoe et al. (2009) question the idea of continuous growth in a world which is finite in terms of resources. They argue that we live in a 'full world' but our socio-economic system was created for an 'empty world', therefore we need to adjust the system. Victor (2008) calculates, using the Kaya equation (IPCC, 2000), that very steep – practically unfeasible - annual decreases in carbon intensity of the economy (3.9%) would be required to meet a 60% emission reduction target by 2050, if GDP was rising at 1.4% a year, and the population would be rising at an annual forecasted rate of 0.7%. Since it may be impossible to control population increases with further policy measures, we should focus on limiting GDP growth in the developed world.

According to Victor (2008), historic data show that "greater decreases in CO_2 intensity do not require faster economic growth" (p. 121),as many would argue. He also points out that decoupling growth and material and energy inputs is not of much benefit, if the rate of growth is greater than the rate of decline in material and energy consumption. As mentioned in Table A, his modelling of the Canadian economy up to 2035 indicates that economic growth need not be a necessary objective for meeting welfare, climate change, and other environmental goals. Similarly to Victor, Sorrell (2010) argues that sustainability is irreconcilable with continued economic growth in the developed world. But he makes a further claim (while also criticizing Victor, 2008) that "a zero-growth economy is incompatible with a debt-based monetary system", in other words, even if we would agree that economic growth should be limited, we would first have to change the system of fractional reserve banking which requires that the amount of money in circulation and the value of goods and services bought and sold must both rise, either through inflation or through consumption, i.e. that both debt and the GDP must rise. As a solution to breaking this growth imperative, Sorrell suggests that the "lending function of banks should be separated from the money creation function and that the latter…should be either solely or largely the prerogative of governments" (p. 17).

Finally, the issue of **quality of life**, in terms of the relationship between positive lifestyle changes and cutting GHG emissions or low/no GDP growth, are discussed by Victor (2008) and the World Future Council (2009). Both of these studies emphasize the significant potential for positive changes from actions to reduce CO_2 emissions- less hectic working lives, better social lives, more physical activity, and better air quality.

[37] These include Solar Energy Generating Systems in California, African gas pipelines, existing long distance HVDC lines, feed-in tariffs, Fingrid electricity imports from Russia to Finland, and the introduction of the Euro.

The use of GDP growth as an indicator for policy is increasingly contested because of its failure to incorporate the quality of life. In 2010, the economic advisory councils of Germany and France produced a report about measuring progress.[38] The report noted the importance of also looking at non-material aspects of human well-being.[39] In its Europe 2020 strategy, the European Commission committed itself to monitoring progress towards the objective of a smart, green and inclusive economy that can deliver high levels of employment, productivity and social cohesion.

Most of the literature talks about tackling climate change while ensuring economic growth. This implicitly or explicitly assumes that economic growth can be sufficiently decoupled from material throughput from energy and resource use. The negative effects from economic growth in terms of environmental degradation and sacrifices associated with it in terms of free time, and evidence that above a certain income level material consumption does not make us happier, leads people to question the desirability of economic growth. According to Tim Jackson, a vocal person in the debate about growth, the story of growth is false, "it is a story about us, people, being persuaded to spend money we don't have on things we don't need to create impressions that won't last on people we don't care about". These ideas are not new. John Maynard Keynes, perhaps the world's most renowned economist, expected people to work less when they got wealthy, to enjoy arts and leisure, but this never happened.

In his book *Why we disagree about climate change*, Mike Hulme makes a plea for using climate change to rethink development as societies and individually in terms of what we really want. Rather than asking "how do we solve climate change", we should turn the question around and ask "How does the idea of climate change alter the way we arrive at and achieve our personal aspirations and our collective social goals" (Hulme, 2009, p. xxix). He notes that climate change is not a problem that can be solved:

"Climate change is not like lead or asbestos in construction – undesirable physical substances to be eliminated and regulated. Neither is climate change simply a social problem seeking a political solution. It is not like slavery or domestic violence; distortions of human relationships to be outlawed and policed" (Hulme, 2009, pp. 328-329).

His book reveals the cultural and ideological elements that underlie climate change positions, showing that climate change is at once a physical phenomenon and a cultural phenomenon based on what we hold sacred, the things we value, and our trust in technology and authorities. It is reflections like these that should inform action. According to Hulme, a global unitary approach to deal with climate change will fail, in terms of the stated objectives for a better world; he believes more can be achieved through coalitions of nations, cities, businesses and NGOs.

De-growth people put well-being and respect for humans and nature before material wealth. In terms of the scheme shown in Figure 3.2, they are in the top-right corner. Most of the world is in the middle area, favouring green growth rather than negative growth. Green growth is embraced by the OECD, national governments, the European Commission and more recently also by newly developing countries such as China. Equality concerns are also rising. Fair trade and the rise of corporate social responsibility are the living evidence of that.

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[38] http://www.sachverstaendigenrat-wirtschaft.de/fileadmin/dateiablage/Expertisen/2010/ex10_en.pdf

[39] The growing interest in measures beyond GDP is documented in an overview of relevant events at the website http://www.beyond-gdp.eu/news.html. It shows that European leaders of the main economies of Europe (UK, France, and Germany) have expressed an interest in alternative welfare indicators. In France, at the request of President Sarkozy, a commission on the measurement of economic performance and social progress has been created, headed by Nobel price laureate Joseph Stiglitz, former chief economist of the Worldbank. In its report, the CMEPSP proposes to shift emphasis from measuring economic production to measuring people's well-being and to broaden income measures to non-market activities.

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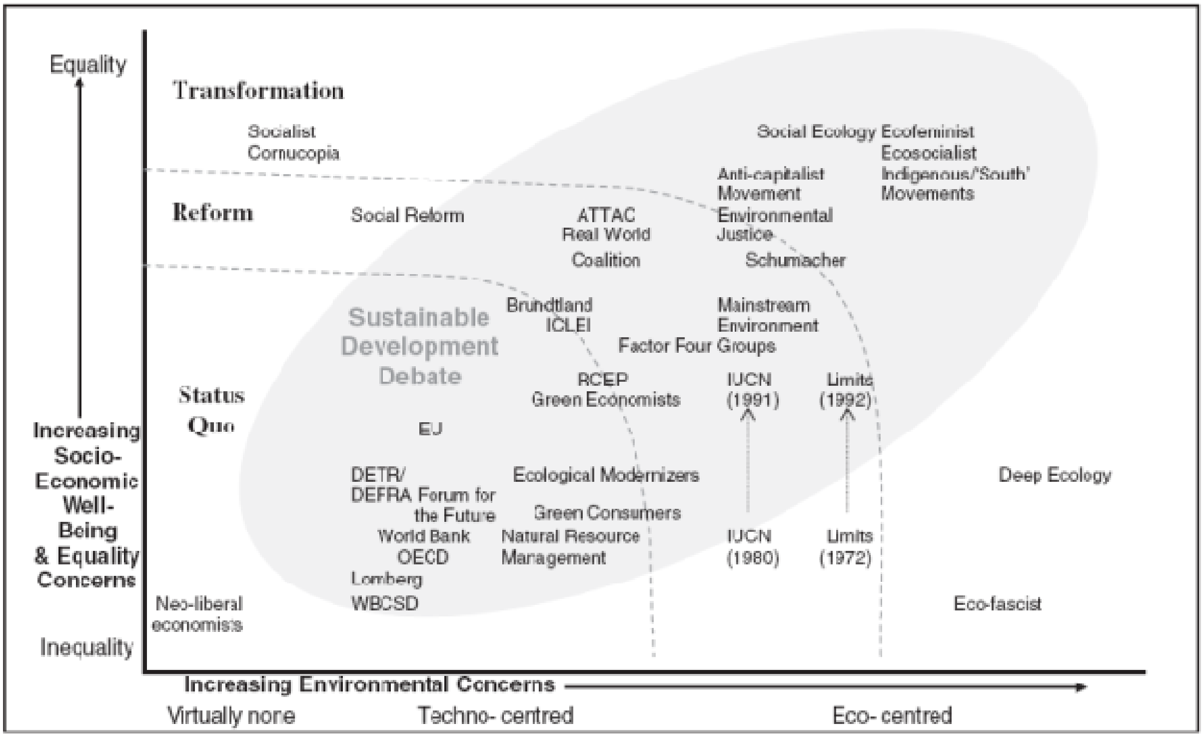

Figure 3.2 **Mapping of views on sustainable development**
Source: Hopwood et al. (2005, p. 41)

Climate change policy may benefit from quality of life and sustainability thinking, something which will be addressed deeper in Chapter 7.

3.4 Other relevant issues

Energy security is an issue closely related to climate change policies for several reasons which are very briefly mentioned in some of the reviewed literature. In some ways renewable energy can be considered more secure than fossil fuels, one, because it inherently involves resources that are renewable rather than exhaustible; two, as it involves less importing of energy, especially from politically challenging areas such as the Middle-East; and three, as it generally relies on more diverse sources of both technologies and energy sources, and geographical locations. On the other hand, solar power and wind power are subject to variability. Solar power can only be generated at day time and wind power only when the wind blows neither too hard nor too soft. Their variability necessitates back up power or electricity storage. Back up power can be provided by other renewables. Hydropower and biofuels are attractive for this. PriceWaterhouseCoopers (2010) believes that a disruption in one, even large, renewable energy system may be relatively quickly compensated by other systems, as long as these are all grid connected. When imported from outside the European Union, renewables may suffer from political energy security risks.

The plan of PWC (2010) of 100% renewable electricity for Europe by 2050 involves importing significant amounts of renewable energy (with some storage capabilities) from North Africa. However, Behrens (2009) (in NEAA, 2009) notes that energy security as a sole focus of energy policy might not increase the share of renewable energy, but instead it could put more coal and gas in the market, with these two fossil fuels being cheaper, more plentiful and less dependent on imports, especially from the Middle-East. Finally, none of the reports really discuss the security of renewable energy from the point of view of meeting demand peaks from intermittent renewable sources, such as wind or solar energy, with the exception of IEA (2010b), which points out that CSP is more secure than PV (because CSP systems can store energy much better and dispatch it when required).

The reviewed literature pays relatively little attention to issues such as **material scarcity** or **recycling**, although in some of the models scarcity is factored in (e.g. Victor, 2008), and some reports, most notably WBSCD (2010), discuss issues such as closed loop manufacturing processes, which aim at eliminating waste. The most notable exception is Giljum and Polzin (2009). One of their main conclusions from their modelling is that policies to decouple economic activity from energy and resource use can be "conductive to economic growth" (p. 17), as resource efficiency measures decrease material costs and reduce unit costs, enabling industries to produce and sell more cheaply. The IEA (2010b; 2010c) is also an exception in considering material scarcity from the point of view of renewable technologies themselves, i.e. do we have enough natural resources to radically increase the use of certain technologies. These two reports also mention recycling of materials used for the technologies in question. Further, regarding recycling, one of the abatement levers quantified in McKinsey (2009) is waste recycling, and the waste sector is one of the industries discussed in detail in the report. Their main conclusion is that realising the full abatement potential of the waste sector would effectively eliminate GHG emissions from waste,[40] with the cost of abatement measures being negative, due to using recycled goods in manufacturing processes, and mature, simple technologies for landfills. About 60% of the abatement potential can be achieved through recycling, according to McKinsey.

3.5 Summary of policy options for climate change mitigation

The reviewed literature contains many suggestions for policies to reduce CO_2 emissions and identifies barriers to large-scale changes in these emissions. These are summarized in this section.

3.5.1 Mitigation policies

There are several approaches to summarizing mitigation policies: by sector, by technology characteristics, and by the general purpose of the policies. Table 3.1 provides an overview of policy recommendations of relevance to five main economic sectors: energy supply, transport, buildings, industry and agriculture. These five 'sectors' are the main producers of CO_2 emissions. Although similar policies to reduce CO_2 emissions can be effective in each of these sectors (such as a carbon price), there are also policies that are unique to each sector. For example, improved building codes to minimize space heating costs (a major source of CO_2 emissions) are relevant to the building sector, but not to transport or energy supply. In other cases, there are areas of overlap in the policy options. For instance, changes to planning design (decrease the size of apartments to reduce heating costs) can reduce energy emissions from the built environment, but changes in urban planning design is also of relevance to emissions from transport.

[40] According to McKinsey (2009), without abatement, annual emissions from the waste sector are projected to increase to 1.7 Gt CO_2 by 2030, growing 0.9 percent per year.

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Enterprise and Industry

Table 3.1 Sector policy recommendations for climate change mitigation: constraints and opportunities

Sector	Policy recommendations	Constraints and challenges	Opportunities
Power sector	Reduction of fossil fuel subsidies; taxes or carbon charges on fossil fuels; Feed-in tariffs for renewable energy technologies; renewable energy obligations; producer subsidies; Direct funding for training more scientists and engineers in the energy sector; More public R&D and more support for private R&D (reversing the downward trend)	Resistance by vested interests may make carbon taxes or charges difficult to implement, and subsidies difficult to remove Lack of certainty over the future pricing of the carbon externality may reduce the incentive to innovate Long learning curves typical for energy technologies Infrastructural lock-in effect strong in the energy sector Lack of competition and strict government regulations may discourage innovation	Markets for low emissions technologies
Transport	Mandatory fuel economy; biofuel blending and CO_2 standards for road transport; Taxes on vehicle purchase, registration, use and motor fuels; road and parking pricing; Influence mobility needs through land-use regulations and infrastructure planning; investment in attractive public transport facilities and non-motorised forms of transport; Applying the ASI-framework (Avoid-Shift-Improve) on motorized transport using various policy instruments41	Partial coverage of vehicle fleet (new purchases only) regarding new standards may limit policy effectiveness; Effectiveness of taxes and pricing policies may drop with higher incomes Rebound effect in terms of vehicle use and increased fuel efficiency Lock-in to existing technologies	Fuel-efficient and low carbon vehicles
Buildings and cities	Appliance standards and labelling; Building codes and certification; Demand-side management programmes; Public sector leadership programmes, including procurement; Incentives for energy service companies; Tax incentives and subsidies for energy efficiency investments; Urban planning with smart growth principles;42 Guidelines evolving towards mandatory requirements; Education and promotion regarding energy use; Information provision	Periodic revision of appliance standards needed; Enforcement of building codes can be difficult; Split incentive (in terms of energy efficiency measures) between building owners and tenants has to be overcome by regulating also existing buildings; One size does not fit all: cities can very different in how and where they have been built (brown, blue, green, red cities)43 and require different solutions; Need for regulations so that utilities may profit even when the aim is lower energy use; Rebound effect and ignorance in terms of energy use and energy efficiency; Institutional information failures must be corrected	New building codes and certification are attractive for new buildings; Retrofitting existing building stock can create a large number of new jobs;44 Government purchasing can expand demand for energy-efficient products; Success factor for energy service company incentives: Access to third party financing

[41] See EEA (2010), Figure 8.2. The ASI-framework is originally from Dalkmann and Brannigan (2007).

[42] Smart growth principles (a fairly recent US development) are: new developments connected to public transport; park and ride systems; bicycle parking at public transport stations; car-free city centers; increased density and mixed use developments (Girardet and Mendonca, 2009).

[43] Brown cities are old cities that have grown gradually, green cities are cities with lots of greenfield construction, blue cities are those that are built in at-risk areas (flooding, sea level rise), red cities are those that have been built more ad-hoc (mostly not relevant for Europe) (WBCSD, 2010).

[44] According to the Clinton Foundation, which has an energy efficiency building retrofit program, retrofits of existing buildings can reduce their energy use by 20-50% (see http://www.c40cities.org/news/news-20070516-fact.jsp, viewed on 7/7/2010).

Sector	Policy recommendations	Constraints and challenges	Opportunities
Industry	Provision of benchmark information; performance standards; subsidies; tax credits Tradable permits; Voluntary agreements	Instability of national policy may hamper international competitiveness; Predictable permit allocation mechanisms and stable price signals important for investments; Success factors of voluntary agreements include: clear targets, a baseline scenario, third-party involvement in design and review and formal provisions of monitoring, close cooperation between government and industry	Benchmarking, performance standards, subsidies and tax credits stimulate technology uptake
Agriculture & forestry	Financial incentives and regulations for improved land management; maintaining soil carbon content; efficient use of fertilisers and irrigation		May encourage synergy with sustainable development and with reducing vulnerability to climate change, thereby overcoming barriers to implementation

According to the McKinsey study the biggest potential for GHG reduction is in agriculture and forestry (12.4 $GtCO_2e$ per year by 2030), followed by power supply (10 $GtCO_2e$ per year in 2030) and industry (7.8 $GtCO_2$). The very large potential for GHG reduction is agriculture and forestry is now well-known.

To achieve GHG emissions, government policies of various kinds are needed. One critique of the mitigation policies summarized in Table 3.1 is that they fail to provide an overall structure that recognizes **the need for different policies for different types of technologies**. As mentioned earlier, Smith (2009) argues that disruptive and radical innovations are required to transform our energy supply and transport systems. This would require a strong coordinating role for governments which are the focus of the policy prescriptions in Table 3.1, but also institutional and coordination failures. These cannot be managed through market failure policies. They include long time horizons, risk and uncertainty, multiple search paths, social adaptation to a new technology, and overcoming lock-in to the existing technological regime.

An alternative to the sector based summary of policies that is given in Table 3.1 is to categorize policies on the basis of their main goal: is the intent to subsidize technology development (technology push) or to create demand for low emission technology (market pull)? Lazarus and Kartha (2009) develop a policy scheme by crossing these two goals of policy with comprehensive or 'generic' strategies and technology specific strategies. The results are summarized in Table 3.2).

Table 3.2 Technology push and market pull climate-related technology strategies

	Technology push	Market pull
Comprehensive strategies	R&D tax credits, matching funds, or other R&D incentives Competitive R&D funds (contests or bidding processes) Instruments for public-private partnerships in R&D Broad R&D "portfolio strategies" Patent/intellectual property rights (support and transfer) Technology transfer protocols Support for education and training	Economy-wide GHG taxes, permits, trading, or standards Removal of subsidies for GHG-intensive activities Sector-specific GHG permits or regulations (e.g. requiring all new power plants as net zero-emission after 20xx) GHG criteria for international finance (e.g., development bank or export credit agency rules) Voluntary ("avoid regulation") GHG programs
Selective technology- specific strategies (pick winners or "clusters" of winners, or eliminate losers)	Targeted government R&D programs Collaborative research programs and support for private R&D Technology cooperation and transfer programs Technology demonstrations Knowledge diffusion (e.g. extension services, marketing and publicity)	Incentives, requirements, and other support for low GHG technologies (feed-in tariffs, portfolio standards for renewable electricity or fuels, tax credits for nuclear and renewable energy, government procurement of efficient equipment or renewable fuels and electricity, etc.) Regulatory (technology-forcing) standards (e.g. emissions standards, appliance efficiency standards)

Source: Lazarus and Kartha (2009), p. 13.

The issue of policy choices is considered in chapter 7, where we will argue that there is a need for both technology push and market pull policies. Technology push policy can help facilitate the creation of new environmentally friendly technologies, but provides little incentive to adopt these technologies (Newell, 2010, p. 263). For adoption, market pull is needed but incentives for innovation from these may be too weak to promote radical innovation, characterised by uncertainty, long-term payoff and problems of appropriating the benefits amongst contributing actors (Jacobsson et al., 2009; Kemp and Pontoglio, 2008).
Regarding the **timing of policy action**, most of the reviewed scenarios do not give timelines for specific action. An exception is the report by PWC (2010) which gives a timeline for developing a smart grid that could link solar plants in North Africa with Europe.

3.5.2 Barriers to change

There are many barriers to change to moving to a low-carbon economy. Table 3.3 gives an overview from three scenarios on specific barriers to the deployment of energy-efficient technologies and suggests policies for overcoming these barriers.

Table 3.3 Barriers to the deployment of energy-efficient technologies and practices

Barrier	Why is this a barrier?	How to overcome the barrier
Low or volatile energy prices	Subsidies Prices do not include environmental costs	Eliminate perverse subsidies globally Put a value on carbon and ecosystem services
High upfront costs and long pay back periods	Most consumers value the present cost of consumption and want their money back in only 1-2 years in terms of energy efficiency investments Lack of capital	Economic incentives (e.g., tax reductions) to decrease first cost Use finance mechanism to leverage investments
Slow diffusion of technologies	Lack of skills, knowledge and support on the use of technologies Fragmented and non integrated industry structures (e.g., building sector) Lack of effective intellectual property rights (IPR) protection Old grid technology	Continuously tighten efficiency standards for lighting, vehicles and appliances Enhance capacity building Ensure IPR protection in accordance with WTO regulations Boost best practice sharing and energy efficiency education (Re-)train architects, construction trades people and inspectors in terms of building energy efficiency Strengthen and extend transmission lines that can bring remote renewable power to population centres Upgrade the grid to use a multiplicity of technologies, both distributed and centralized; take advantage of active demand management
Entrenched business models	Lack of incentives for energy companies to reduce customer demand	Internalize carbon prices in energy services Financially reward end-user energy efficiency measures Promote energy service companies Make it more profitable for e.g. electric utilities to invest in renewable energy and efficiency than to invest in new fossil fuel plants or continue operating existing ones
Diversity of consumers and energy needs	No single solution fits all	Promote voluntary sectoral initiatives and negotiated agreements
Information failures	Lack of information or imperfect information regarding future energy prices and energy efficiency alternatives Often individual efficiency alternatives are small, and mainly matter in aggregate	More effective technology standards (e.g., building codes) Product energy labelling Advice on smart energy metering
Split incentives (principal agent problem)	Those making decisions on energy efficiency do not benefit (e.g., construction companies vs. building owners vs. tenants)	Provide clear information and incentives (e.g., tax rebates, mortgage discounts, rebates, preferential loans) Establish an energy-rating system for all buildings at the time of sale

Barrier	Why is this a barrier?	How to overcome the barrier
Uncertainties on investment and risks	Uncertainties add a premium to investments	Economic incentives to reduce costs and risks Develop robust energy and carbon markets Establish stable regulatory frameworks
Consumer behavior	Low priority of energy efficient investments Lack of awareness and information on energy consumption and costs	Improve product information Incentives to remove and replace old equipment Raise education and awareness on energy efficiency
Investment costs higher than expected	Projects do not include all transaction costs	Boost best practice sharing and energy efficiency education

Source: WBCSD (2009); Worldwatch Institute and the Fletcher School (2009); McKinsey (2009).

The table identified ten barriers: low or volatile prices, high upfront costs and long pay back times, slow diffusion of technologies, entrenched business models, diversity of consumers and energy needs, information failures, split incentives, uncertainties on investments and risks, consumer attention being focussed on non-energy issues and investment costs being higher than expected. The diversity of consumer needs will make some consumers opt for powerful cars. It is important therefore that there are green powerful cars. The use of energy efficiency labels per car category is useful for informing consumers about the energy efficiency of cars within a class but does not really promote the buying of light-weight cars. Taxes on the basis of vehicle weight and CO_2 emissions are a way of dealing with that problem.

An issue that is not worked is that there **are also barriers to effectively dealing with the barriers.** Policy making is a difficult business, because of uncertainty, information asymmetries and use of power by special interests -- issues which play themselves out over and above the barriers and the solutions to them. In chapter 7 this issues is being addressed and worked out in terms of policy recommendations such as reducing uncertainty about effects (through assessment and tests), avoid regulatory capture and to maximise policy learning. Another important issue for policy is that should provide a continuous incentive for innovation. Ways to do this are to make energy-efficiency labels dynamic, regularly upgrade energy standards upgraded, to signal future requirements and to make use of economic instruments. Some of the scenarios provide some useful advice in this regard, such as having renewable energy deployment targets for after 2020, complementing the ETS with measures that reinforce incentives to invest in low/zero carbon resources, rule out investment in long-lived high carbon generation and deal with market barriers to energy efficiency measures (ECF, 2010).

3.5.3 Conclusion on mitigation scenarios

Table 3.4 below summarizes some of the main points made in the reviewed mitigation scenarios, while also evaluating their potential usefulness for current European climate policy. We indicate the studies' view on contested issues such as CCS and the role for renewables up to 2020 and present examples for immediate policy action from the studies. Table A at the end of the report gives further detail on the scenarios. The content of the summary table will not be discussed again, but states salient findings and the usefulness of the study for policy.

The studies touch upon the link between climate change and demographic change and take account of changing resource scarcity for fossil fuels but do not examine these in much detail, which is why we won't discuss those findings.

Table 3.4 Summary of reviewed mitigation scenarios (see also Table A in Appendix)

Scenario and focus	Examples of agreements and disagreements	Examples of immediate policy action focus	Potential usefulness for EU climate policy
Giljum and Polzin (2009) *Decoupling economic activity from energy and resource use*	Critical of emphasis on efficiency improvements, they should be coupled with behaviour change	Improving resource efficiency, e.g. through establishment of 'resource efficiency agencies' advising firms, and by implementing resource accounting systems for firms and industries; rebound effect has to be taken into account	Limited use for climate policy, but interesting in terms of the topic of decoupling
National Intelligence Council (2008) *One scenario focussed on "post-petroleum age"*	Renewables will not have a strong role in the next 20 years; CCS important later	No climate related policies suggested	Lacking vision for climate policy
Worldwatch Institute and the Fletcher School (2009) *Global transformational scenario, low carbon future*	Major contribution from renewables in the next 20 years feasible (most scenarios do not adequately model in their potential)	Policies to overcome barriers and path dependencies; Phasing out existing carbon-emitting capital stock and fossil fuel subsidies; A greater number of aggressive targets for energy efficiency improvements and renewables required now; Feed-in tariffs	Good for justifying strong support for renewables
McKinsey (2009) *Five scenarios of global emission pathways, with three of them showing increase in emissions*	Major contribution from renewables in the next 20 years feasible; CCS important later	Policy targets: Overcoming barriers to energy efficiency improvements; Long-term incentives for low carbon technologies; Linking GHG abatement in forestry and agriculture to overall development agenda	Very good on abatement levers; few specific policy recommendations, but otherwise very detailed
World Bank (2007) *Global economic scenarios, where climate change is an externality, potentially threatening growth*	Renewables will not have a strong role in the next 20 years	Removing barriers to behavioural change - e.g. transaction costs, organizational inertia, and a lack of reliable information - through regulation (for example, minimum standards for buildings and appliances), labelling, and sharing best practices, and financing the upfront costs of efficiency improvements; International framework for emissions trading to encourage energy efficiency, technological cooperation to ensure more rapid adoption, action to reduce deforestation, and assistance to poor developing countries to promote adaptation	Too general
International Energy Agency (2010d) *Looks at the effect of current climate policies and "new policies" (Copenhagen pledges) on emissions*	Major contribution from renewables in the next 20 years feasible; CCS important later	EU Directive on the geological storage of carbon dioxide; Extended emission targets for passenger light-duty vehicles and light commercial vehicles by 2020; Enhanced support to alternative fuels; National EV targets; Aviation and international maritime shipping in ETS from 2013; Directive on energy efficiency including the development of inverters for electric motors, high-efficiency co-generation, mechanical vapour compression and emergence of significant innovations in industrial processes; Nearly zero-energy buildings standards mandatory for new construction as of 2020 and zero-carbon footprint for all new buildings from 2018	A detailed, but relatively narrow focus
Victor (2008) *Model of Canadian economy with low/no GDP growth*	Too much reliance on technology should be avoided; Critical of emphasis on efficiency improvements, they should be coupled with behaviour change	Policies required in investment (using taxes to discourage excessive investment in new capital), productivity (redirecting increases in productivity to something other than throughput, e.g. leisure time), and technology (comprehensive technology assessment for new technologies)	Good in terms of examining planned low or no growth in developed countries
World Business Council for Sustainable Development (2010) *Sustainable growth scenario*	Major contribution from renewables in the next 20 years feasible; Europe-wide super electricity grid; CCS important later	Examples of policies for 2020: Regular building audits by governments to measure performance, identify improvement opportunities, and establish implementation priorities in most developed countries; Mandatory standards for buildings' thermal integrity and heating systems across the OECD; Mandatory recycling and optimized packaging in OECD countries	Comprehensive, not considering challenges enough
PriceWaterhouse Coopers (2010) *Roadmap for 100% renewable electricity production for Europe and North Africa*	Major contribution from renewables in the next 20 years feasible; Europe-wide super electricity grid	Rewriting of energy policy and legislation is necessary to change the rules and incentives; For example, guidance for the implementation of Article 9 of the Renewables Directive dealing with imports of electricity, and the development of a new directive on grid regulation mandating long term EU level planning of grid infrastructure (enabling more ambitious short-term national targets for renewable energy)	Very good in terms of transformation of the European energy system, contains a detailed map of specific policy milestones for short term, medium term and long term
NEAA & Stockholm Resilience Centre (2009) *Meeting the challenges of population growth & climate change; low carbon energy system for the EU*	Major contribution from renewables in the next 20 years feasible; Europe-wide super electricity grid; CCS important later	Bio-energy should only be used when no low-carbon alternatives currently exist and where it pays most (e.g. road freight transport or aviation); Currently available no-regret technologies, such as heat pumps, solar PV and wind power should be stimulated in a coordinated way; Emission standards need to be set for new power plants, a clear target for phasing out fossil power	Good; specific for Europe
Lazarus and Kartha (2009) *Examines metrics for technology development to decrease energy related carbon emissions*	CCS potentially important later	No specific short-term policy targets, but necessary longer term objectives for low carbon technology development include (in addition to R&D): Building technological capacity; Establishing new institutions; Mobilizing political constituencies; Creating new classes of assets; Opening financing channels; Eliminating subsidies and other policy biases in favour of incumbent technologies	Good on potential metrics for climate policy assessment
International Energy Agency (2010b) *Potential of concentrating solar power (CSP)*	N/A	Establishing an equitable environment for CSP development through feed-in tariffs or binding renewable energy portfolio standards; Encouraging state-controlled utilities to bid for CSP capacities; Streamlining permit procedures for CSP plants and access lines; Offering suitable land and access to grid or water resources, and waiving land property and other taxes, as additional means for quick-start deployment; Developing incentive schemes for solar process heat and fuels, not just electricity; Progressively eliminating subsidies for fossil fuels	Good for the purpose of backing CSP; contains specific policy milestones
International Energy Agency (2010c) *Potential of photovoltaics (PV)*	N/A	Policy areas: Creating a policy framework for market deployment now and in the next decade, including incentive schemes to accelerate market competitiveness; Improving financing models and training and education to foster market facilitation and transformation	Good for the purpose of backing PV; contains specific policy milestones

Scenario and focus	Examples of agreements and disagreements	Examples of immediate policy action focus	Potential usefulness for EU climate policy
International Energy Agency (2010a) *Energy technology perspectives and policies to accelerate low-carbon technologies*	All technologies on low-carbon portfolio are needed Global climate change goals. Carbon pricing important but not sufficient for a low-carbon technology transition.	The report proposes a twofold to fivefold increase in public RD&D spending amounting to between 20 and 50 billion USD annually.	High, especially the discussion about tailoring policies to the stage of technology development.
Shell (2010) *Scenarios for energy and resource use (stories about future)*	Energy security may work strongly against climate change policy. Shell expects fossil fuels to provide more than half of primary energy use in 2050.They anticipate bigger barriers for renewables and nuclear than for fossil fuels.	No policy recommendations are made but a climate treaty would help to restrain energy consumption and help to accelerate low-carbon investments.	The scenarios are useful for exploring the future, pointing to differences in interests and sources of conflict.
European Climate Foundation (2010) *Identification of low-carbon pathways for the power sector* *Attention is given to security of supply, economic recovery, prosperity and price stability*	Full carbonization of electricity by 2050 is necessary and possible with existing technologies and those under development. Changes in network infrastructure and the way it is operated are critical to meeting the 2050 emissions objective. CCS should be introduced as quickly as possible. Socialisation of part of the risk is necessary. No need for an overhaul of existing arrangements: policies can build on the single energy market agenda and the climate policy package.	Convert the non-binding 2020 efficiency goal into a requirement; revise the Energy Services Directive to support a tripling of the energy efficiency policy impact; avoid investments in high-carbon power plants; change the narrative: energy efficiency is a zero-carbon supply side resource; increase interconnections between power systems and optimise the use of resources amongst Member States; significantly improve demand response through smart grid applications; request Member States to come forward with long term targets for deployment of key renewable generation technologies (beyond 2020) and adopt parallel measures for CCS; introduce new provisions requiring Member States to identify a long term planning generation and demand-side resource mix out to 2050 that can be used to underpin strategic network development and is consistent with decarbonisation objectives. The report focuses on the power sector but notes that the heat and transport sector should make a large-scale shift to the use of decarbonised electricity.	Very high. The report contains a wide mix of concrete proposals for policy (both at the EU and MS level), based on a very good understanding of energy markets and what is keeping back investments in low-carbon technologies.

3.6 Adaptation to climate change

The above sections have concentrated mostly on climate change mitigation, or technologies to reduce GHG emissions. However, many argue that adaptation, or to measures to mitigate the *consequences* of climate change, such as permanent flooding from rising sea levels, should get a bigger priority, in particular at the EU member state level (Henderson, 2009; ADAM, 2008; EEA, 2007). Environmentalists tend to dislike discussions about “adaptation” because it takes attention away from mitigation, but the need for adaptation will be inevitable due to past GHG emissions, which have already created a ‘lock-in’ into some undesirable climate changes (Shaw et al. (2007).

The Global Humanitarian Forum (2009) has estimated current global annual economic losses from climate change at over US$125 billion, with expected losses up to US$340 billion per year by 2030. Henderson (2009) makes a business case for climate change adaptation in saying that adaptation can help manage such costs and also provide ‘green growth’. She also argues that regional and local planning and urban design can considerably reduce risks from extreme weather events, for example by means of green infrastructure (e.g. gardens, parks, green corridors, green roofs and walls) and blue infrastructure (water bodies, rivers, streams, floodplains and sustainable drainage systems). New developments should take future climate into account, not historic climate, and sharing of best practice, e.g. within Europe, can be very efficient in disseminating knowledge. Further to this, ADAM (2008) points out that bottom-up processes of learning have to be incorporated with top-down high level policy strategies, and climate change adaptation should be mainstreamed though different sectors and policy areas.

As discussed in Chapter 2, without action to reduce GHG emissions over the near future, IPCC (2007a) predictions for Europe include an increasing incidence of winter floods, flash floods, coastal flooding from rising sea levels, droughts, intense heat-waves, and forest fires. The secondary effects include greater exposure to vector- and food-borne diseases, shifts by region in the distribution of forests and crop suitability and productivity (with increases in some areas and decreases in others), water availability and water stress. Natural ecosystems and biodiversity could also suffer if many species are incapable of rapidly adapting to changing environmental conditions.

The adaptive requirements differ by region and sector. The most vulnerable regions in Europe are Southern Europe, the Mediterranean Basin, and the Arctic (EC, 2009). In agriculture the increasing likelihood and severity of extreme weather events will considerably increase the risk of crop failure (EC, 2009). Droughts will increase the demand for water and intensify problems of water availability which already poses a problem in many parts of Europe. Tourism is likely to suffer from decreasing snow cover in mid-latitude Alpine areas and from increasing temperatures in Mediterranean regions (EC, 2009). Stronger flood defences will be needed to protect infrastructure (buildings, transport, energy and water supply) and human life. There are also positive effects: increasing atmospheric CO_2 and rising temperatures may allow earlier sowing dates, enhance crop growth and increase potential crop yield in northern areas. Tourism could also increase in some areas while it declines in other regions.

Table 3.5 gives the IPCC view on adaptation options and strategies in Europe related to water and human health in terms of floods, heat waves and water stress.

Table 3.5 Adaptation to climate change in Europe – Water and human health

Issue	Options and strategies for dealing with floods	Options and strategies for dealing with water stress	Options and strategies for dealing with heat stress
Water	Reservoirs in highland areas and dykes in lowland areas; expanded floodplain areas; emergency flood reservoirs; preserved areas for flood water; flood warning systems	In-stream reservoirs; wastewater reuse desalination; water conservation; reduction of leaky water systems; water pricing; new crops requiring less irrigation; integration of strategies to water management	

European Commission
Enterprise and Industry

Issue	Options and strategies for dealing with floods	Options and strategies for dealing with water stress	Options and strategies for dealing with heat stress
Human health	Public flood monitoring systems; evacuations from lowlands; waterproof assembling of hospital equipment; establishment of decision hierarchies between hospitals and administrative authorities		Health early warning systems; preventive emergency plans; mitigation of 'heat islands' through urban planning; adaptation of housing design to local climate; expanding air conditioning; shifts in work patterns; mortality monitoring

Source: IPCC (2007a: 559-562).

Table 3.6 presents options for the European agriculture, tourism, transport and energy sectors, also in terms of policy. These suggestions have also been taken from the IPCC 4th assessment reports of 2007. Together Table 3.5 and 3.6 point out the many climate change adaptation options and strategies that are available. More than mitigation options, adaptation measures have to be customised to the local context and often represent a unique solution to the problem at hand. To help architects, city developers and water authorities with climate adaptation, a number of principles for climate adaption have been developed (TCPA, 2007). These climate adaptation principles are:

- Seek opportunities to incorporate adaptation into new and existing developments
- Work in partnership with communities
- Incorporate flexibility to deal with changing risks
- Understand existing vulnerabilities to climate and identify critical thresholds
- Identify key climate change risks using the latest climate change scenarios
- Look for no-regrets, low-regrets, win-win and adaptable measures to manage climate risks
- Adopt a sequential and risk-based approach to development decisions
- Avoid actions that will make it more difficult to cope with climate risks in the future
- Review your adaptation strategy regularly (TCPA, 2007).

Climate adaptation technologies are being supported through EU programmes for innovation and through national programmes, but it is unclear how much support has been granted. There is a need for knowledge sharing and there is also a need for helping developing countries deal with climate change, where the capability to adapt to climate changes is much smaller, while the consequences are more severe.

Table 3.6 Climate change adaptation in Europe for four sectors

Sector	Options/strategies	Policy framework	Constraints (normal font) and opportunities (*italics*)
Agriculture	Adjustment of planting dates and crop variety; crop relocation; improved land management	R&D policies; reform of EU agricultural policies and related institutions; training; capacity building; crop insurance; financial incentives, e.g. subsidies and tax credits	Technological and financial constraints; access to new varieties; markets; *Longer growing season in higher latitudes; revenues from 'new' products*
Tourism	Diversification of tourism attractions and revenues; shifting ski slopes to higher altitudes and glaciers; artificial snow-making; promoting changes in temporal patterns of tourism; efficient cooperation with local authorities regarding risks	Integrated planning (e.g. carrying capacity; linkages with other sectors); financial incentives, e.g. subsidies and tax credits	Appeal/marketing of new attractions; financial and logistical challenges; potential adverse impact on other sectors (e.g. artificial snow-making may increase energy use); *Revenues from 'new' attractions involvement of wider group of stakeholders*
Transport	Cleaner technologies; adapting behavior; design standards and planning for roads, rail and other infrastructure; raising standards in design of new vehicles; capacity building in response to incidents, e.g. floods	Integrating climate change considerations into national transport policy; investment in R&D	Financial and technological barriers; *Improved technologies and integration with key sectors, e.g. energy*

Sector	Options/strategies	Policy framework	Constraints (normal font) and opportunities (*italics*)
Energy	Enhancing the interconnection capacity of electricity grids; energy efficiency; use of renewable sources; reduced dependence on single sources of energy; using more decentralized electricity generation systems	National energy policies, regulations, and fiscal and financial incentives to encourage use of alternative sources; incorporating climate change in design standards	Access to viable alternatives; financial and technological barriers; acceptance of new technologies; *Stimulation of new technologies; use of local resources*

Source: IPCC (2007b: modified from Table 4.1) and IPCC (2007a: 559-562).

3.7 Role of forests and agriculture

Forests are left out of the discussion in many studies, but others discuss the low-cost but significant contribution that reforestation and the prevention of deforestation can make to ameliorating climate change. The study by McKinsey (2009) provides estimates about the magnitude of the abatement potential. They find that halting tropical deforestation, reforesting marginal areas of land and sequestering more CO_2 in soil through changed agricultural practices provide an opportunity of 12.4 $GtCO_2e$ per year in 2030. To put this in perspective: the abatement potential of the power sector is estimated at 10 $GtCO_2$ per year in 2030 and the abatement potential of transport is estimated at 3.2 $GtCO_2e$. The potential of terrestial carbon is thus very high, almost as high as the abatement potential of all energy efficiency measures combined which is 14 $GtCO_2e$. The study, however notes that capturing those opportunities is not easy. 90 percent of the potential is in the developing world. Saving 170 millions of forests amounts to saving a forestry area twice the size of Venezuela. Foresting 330 million hectare of marginal land amounts to a total area the size of India.

Stopping deforestation hasn’t got the attention it deserves. Stern (2007) reminds us of the estimate that almost a fifth of non-fossil fuel related emissions (which in themselves are 40% of total current CO_2e emissions) come from deforestation. Sachs (2008) and McKinsey (2009) both argue that prioritizing forest and agriculture related issues in emission reduction policies is important, and TEEB (2009) and UNU-IAS (2008) focus on the new United Nations REDD (Reducing Emissions from Deforestation and forest Degradation) instrument, which, according to TEEB could lead to a halving of deforestation by 2030, if successful. As mentioned above, Girardet and Mendonca (2009) argue for the importance of biosequestration of carbon. They emphasize that with reforestation, the focus should be in mimicking natural forest ecosystems, rather than in monoculture, and they also further the idea of using biochar, produced by pyrolysis of organic waste material.

Regarding agriculture and the issue of carbon, Girardet and Mendonca (2009) argue for scrutinizing modern food production, both in terms of their dependency on fossil fuels, and in terms of the one-way transportation of huge amounts of carbon (in food) away from farmland, where it would be needed, to cities, where it ends up as a waste issue. Additionally, they further the idea of using salt-loving plants (called halophytes, e.g. mangroves and salicornia) that can be irrigated with salt water. These plants can help increase agricultural area for especially biofuel production significantly, so that using them could increase the world’s irrigated agricultural area by up to 50%.

3.8 Conclusions

Some general conclusions from the literature are that European policy should focus on the following:

1. Mainstreaming climate change policies and thus, incorporating both climate change adaptation and mitigation into other policies
2. Encouraging EU member states to align their policies with EU goals in terms of climate change
3. Creating long term, transparent policies
4. Enabling a transformation of the EU energy and transport sectors and urban planning by concentrating on removing known barriers to it

5. Accepting that renewable energy sources have potential to supply much of Europe with electricity, as long as the necessary infrastructural changes, policy, and financing are taken care of
6. Focusing on the merging of European electricity and transport sectors which – through increased energy storage - can enable power demand to follow supply, rather than the other way around
7. Increasing R&D support, but not relying too much on this to take care of the necessary technological innovation
8. Considering behavioural changes – e.g. in terms of consumption of energy and resources - necessary to fight climate change, and especially in combination with policies to encourage energy efficiency
9. Questioning the current policy view according to which high GDP growth can never be a bad thing, and low to zero GDP growth is always undesirable.

A deeper discussion of policy issues is provided in Chapter 7.

4 DEMOGRAPHY AND CLIMATE CHANGE

4.1 Introduction

Demographic change in Europe, through both population decline and population ageing, is often viewed as a threat to the competitiveness and economic sustainability of the European Union (Beets, 2008; Jones and Hayden, 2009b). Economic growth is expected to decline due to a fall of the working-age population (aged 15 to 64) of the European Union by 1 to 1.5 million every year after 2015 (Jones and Hayden, 2009a). At the same time, the retirement-age population over 64 will be increasing very year, resulting in an increase in the number of dependent retirees per person of working age. This ratio is expected to increase from approximately four workers per retiree in 2008 to 2.6 workers per retiree in 2030 (EC, 2008).

The main demographic challenge for the economy is from the combination of a shrinking workforce and an increasing dependency ratio. This problem can be addressed by increasing the labour force participate rate and retirement ages by several years in most EU countries. In 2007, only 50% of men and 40% of women were in employment at age 60, allowing ample room for increasing labour supply by increasing labour force participation between 60 and 64 and by delaying retirement. Related problems, such as concerns over the skills of older workers turn out to be largely illusionary and due to cohort effects as shown below.

Demographic change also has potential benefits for Europe in respect to addressing climate change. First, a decline in the European population will make it easier to reduce GHG emissions. This is a basic result of the IPAT equation (I (GHG emissions) = population * affluence (average income per capita) * technology (the GHG intensity of economic activity). A declining population reduces P, resulting in a fall in GHG emissions for a given level of A and T (Dietz and Rosa, 1997).

In addition, a declining or stable population could act to increase the allowable GHG emissions of Europeans. We assume that international agreement for a sustainable level of CO_2 emissions will be based on an equity principle that will limit per capita emissions to 1 tonne per person by 2050, using national populations in 2000 (slightly after Kyoto) or between 2008 and 2010 (See Chapter 2). If the EU-27 population grows, as expected, by 4% with immigration (EC, 2008), there will be only a minor fall in the per capita emissions budget to 0.961 tonnes per capita. However, a falling population to 416 million by 2060 without immigration would increase the per capita budget to almost 1.2 tonnes. Alternatively, the 'excess' could be used to reduce emissions more quickly and at less cost. In contrast, the population of the United States is expected to grow from 310 million in 2008 to 420 million in 2050. This will decrease the sustainable per capita emissions for the United States from 1 tonne to 0.74 tonnes, increasing the difficulty of meeting emission targets.

In addition to the immediate positive effect on reducing emissions through a decline in population, demographic change can affect GHG emissions through three mechanisms that are related to changes in the population age structure. The first effect is due to changes in the demand for goods and services that produce GHGs, due to an increase in the population share of older cohorts (65 and over) and a decline in younger cohorts. The second factor is through a decline in savings for investment in innovation, as populations move from high savings rates between 45 and 60 years of age to drawing down on savings during retirement. The third effect is on the innovation potential to develop zero carbon energy technologies. Demographic ageing could reduce this potential if older researchers and employers are less innovative than younger researchers and employees.

This chapter first summarizes expected changes in the population and age structure of the European Union between 2000 and 2050 or 2060. The following sections then examine each of the three mechanisms by which an ageing population could influence European GHG emissions. Unfortunately, earlier assumptions on the beneficial impacts of ageing on consumption and consequently GHG emissions (see Pearce, 2010), or on savings, may not be true. On the other hand, increasing educational attainment and workforce participation rates should mitigate concerns over the innovative potential of the European workforce.

4.2 Demographic Changes within the European Union

The most important estimates of future demographic change within the European Union are the EUROPOP estimates from 2004 and 2008. The EC (2008) summarizes the results of the EUROPOP estimates of population growth in the EU-27 countries between 2008 and 2060. A separate report by Giannokouris (2008) gives results for 2050. Compared to the previous EUROPOP estimate of 2004, the 2008 estimates adjust for the effect of delayed child bearing, which gives higher and arguably more realistic Total Fertility Rates (TFR) of 1.7 children per woman[45] compared to the EUROPOP 2004 estimates. The EUROPOP 2008 estimate also increases, over time, the average life expectancy at birth. The EUROPOP 2008 population estimates are given both with and without net migration into the EU-27, although the estimate with immigration assumes that net immigration will converge on zero by 2050.[46]

With immigration, the EU-27 population is estimated to increase from 495.4 million in 2008 to 520.7 million in 2035, before falling to 515.3 million in 2050 (Giannakouris, 2008), for a net gain in 2050 of 19.9 million people (+4.0%). By 2060, the population is expected to further decline by almost one million per year to 505.7 million. Without net immigration, the population of the European Union is expected to start shrinking in 2012 and fall to 416.5 million by 2060, for a net loss of 78.9 million (-15.9%). For comparison, estimates for the United States predict an increase of 35.9% from 308.9 million to 419.9 million in 2050 (US Census Bureau, 2004). This increase could be overestimated, since it is largely due to high expected TFRs among Hispanic, black, and Asian populations, plus Hispanic immigration, with only a 4.8% increase in the non-Hispanic white population. Over time, the birth rates for the other populations could fall to resemble that of non-Hispanic whites.

Future population estimates are sensitive to different assumptions about immigration, total fertility rates, and average life expectancy. For example, using different assumptions, EUROPOP 2004 estimated a fall of 16 million in the EU-27 population by 2050, compared to an increase of 20 million in the EUROPOP 2008 estimate. Immigration is subject to national government policy, and could vary considerably. The expected fertility rates could also be too low, particularly in the new member states.

Even though one needs to be cautious in interpreting the estimates, the general trend for either a roughly stable or declining population is likely to hold. It is very unlikely that Europe will undergo a period of rapid population growth, as expected for the United States. Furthermore, a shift in the population structure towards a higher percentage of people over 64 is largely unavoidable. The EUROPOP 2008 study estimates that the share of the EU-27 population aged 65 or over will increase from 17.1% in 2008 to 30% in 2060 (84.6 million to 151.5 million). The number over age 80 will increase threefold, from 4.4% of the EU-27 population in 2008 to 12.1% of the estimated population in 2060 (Giannakouris, 2008). Only unrealistically large increases in net migration or the fertility rate could alter the increase in the share of older cohorts. This increase is also expected in all European countries.

4.3 Ageing, Consumption, and GHG emissions

Early research on the effect of demographic ageing suggested that an older population structure could have significant potential benefits in respect to reducing GHG emissions, based on differences in consumption patterns between younger and older cohorts. For example, research on cohorts that reached retirement age in the 1960s and 1970s suggested that older cohorts consumed less than younger cohorts and saved more (Higgs et al, 2006). However, more recent research suggests that any potential benefit from an older age structure could depend on additional factors.

[45] The total fertility rate is expected to vary considerably by country within Europe and be below average in all ten new member states plus Germany, Portugal, Italy, Spain, Greece and Austria. Higher than average fertility rates are expected in the Netherlands, Belgium, Finland, the United Kingdom, Denmark, Sweden, Ireland, Norway, and France.

[46] This convergence on zero can be justified by a gradual fall in emigration pressure from immigrant source countries, as the income difference between the EU and the source countries declines with economic development in the latter.

An important factor in the effect of older cohorts on GHG emissions is the income and consumption patterns of retirees. An analysis of the 1998 and 1999 Consumer Expenditure Interview Surveys in the United States found that the income of retired couples fell by 26.5% compared to non-retired couples, which would reduce GHG emissions. A fall of 20% was noted for Canada (La Rochelle- Côté et al, 2010). In the American study, expenditures on private transport (almost entirely by automobile) fell slightly more, by 33%, but expenditure on vacations fell by only 7.5% (Paulin and Duly, 2002). In terms of the percentage of income, vacation expenditures increased. As vacations are increasingly by air, a shift from car use to air travel among retirees could increase GHG emissions. A more recent study for Canada found that consumption per individuals over 70 years of age (instead of for households) only decreased by 5% compared to the consumption of adults in their 40s (Lafrance and La Rochelle- Côté, 2011). This suggests that any potential savings in GHG emissions could be fairly small, although this study did not disaggregate consumption into categories for which GHG emissions could be estimated.

Several studies have used variations of the IPAT equation to model the effect of ageing and other factors on GHG emissions. An estimate for the United States found that population ageing could substantially reduce CO_2 emissions, largely by reducing the labour supply and consequently the income of retirees and economic growth (Dalton et al, 2008). A similar model for nine global regions, including the EU, found that ageing could have a potentially large effect on emissions, with long-term reductions of up to 20%. This was primarily due to lower labour force participation rates, resulting in slower economic growth (O'Neill et al, 2010). One disadvantage of these models is that they do not examine different consumption patterns among retirees and they assume full employment and consequently unrealistic constraints on the labour supply.

Three studies that have looked at the effect of age structure on GHG emissions, using data for European countries or for other developed countries, find that an increase in the share of the population over 65+ will *increase* GHG emissions, after controlling for other factors such as GDP, the change in the total population, and other factors. York (2007) examines the effect of age structure on aggregate energy consumption (a proxy for GHG emissions) in 14 European countries and finds that the percentage of the population that is 65+ has a significant positive effect on total energy consumption, with a 1% increase in the share of this cohort increasing energy use by 0.87%. Liddle and Lung (2010), in a study of 13 European countries plus four other developed countries, examined the effect of population shares in four age cohorts on aggregate CO_2 emissions and CO_2 emissions from transport. They found no effect of the population share of 65 – 79 year olds on either outcome. However, they did find that the population share of 65 to 79 year olds increased residential electricity consumption. The effect on GHGs would therefore depend on how electricity was produced – whether by burning coal or petroleum, with high GHG emissions, or from hydroelectric or nuclear plants, with low GHG emissions.

The most relevant study for Europe on the effect of ageing on GHG emissions is by Kronenberg (2009), who uses micro data from a German household consumption survey to estimate the consumption patterns of different age cohorts. These patterns are then linked to data on the GHG emissions of 58 different product groups and to different sources of domestic energy, with results given for methane, N_20, and CO_2 emissions. Kronenberg then models the effect of consumption patterns by age cohort on German GHG emissions between 2006 and 2030. Since the main demographic change is an increase in the share of older age cohorts, the models estimate the effect of ageing in Germany on GHG emissions. The results show that ageing will increase GHG emissions by 2.5% up to approximately 2020, with a fall afterwards. However, age-related emissions in 2030 will still be slightly higher than emissions in 2006. The increase with ageing in GHG emissions is due to greater use of domestic heating and electricity, which more than compensates for a decline in emissions from automobile use. Two variants of the model show that a shift in national income from working age populations to retirees (for instance through more generous pensions) will increase emissions, while policies to encourage public transit use among all age cohorts would be far more effective in reducing emissions.

Kronenberg's model assumes that consumption patterns by age cohort remain constant, whereas other research suggests that the consumption patterns of older cohorts have been changing over time (Higgs et al, 2006). Nevertheless, some of the main drivers of the age effect in this study and the research by York (2007) and Liddle and

Lung (2008) are likely to continue into the future. This is an increase in the time spent at home, requiring more heating, and smaller households, which increases per capita domestic energy use.

The household effect should continue into the future, even with an increase in lifespans, due to the strong preference of older people to remain independent. In 2001 within the EU 27, over 90% of people aged 80-89 and almost 80% of those over 90 were still living in private households (EC Demography Report, p83, 2008). In so far as older people live with their children, this could reduce GHG emissions. Yet this effect will be outweighted by an expected increase in single person households. EUROPOP 2008 estimates that in 2050, 35.0% of EU-27 households will be single person households, compared to 28.8% in 2001, mostly due to an increase in single retirees.

4.4 Finance for innovation

A transition from current dependence on fossil fuels to zero carbon energy sources will require a large shift from consumption to investment (Jackson, 2009). Demographic change in Europe can influence the available supply of capital for investment in several ways.

First, an increasing dependency ratio will absorb resources that could have been used for investment in innovation, while shrinking the share of the population in the high savings cohort of 45 -64 years of age, further reducing the supply of capital available for investment. Some investment will need to be diverted from other purposes to taking care of older age cohorts. This requires funding pensions, health care, and long term care. Standard and Poor (2010) estimates that the cost of paying for these three age-related benefits in 2050 in developed countries will require 5.8% of total GDP, with 3% for pensions, 1.5% for increased health care costs from ageing (this removes a much larger increase for technology driven increases in health care costs), and 1.3% for long-term health care.

Higher retirement ages and worker participation rates for older workers will help reduce the cost of pensions, the single largest component in the Standard and Poor estimate.

Whether or not retirees provide a source of savings for investment in zero energy remains to be seen. Borsch-Supan (1992) reported higher saving rates among retirees than among other age cohorts in Germany between 1978 and 1983, which would have a positive effect on the supply of savings for investment if it continued for more recent cohorts. In contrast, the share of retirement income spent on consumption versus savings is likely to increase among retirees over the next few decades, due to changing attitudes. The 2004 British Social Attitudes Survey found that 27% of people born before 1934 (70 at the time of the survey) intended to reduce spending and pass an inheritance to their children. This rate fell to 10% among the cohort born between 1945 and 1955 and to 9% among the cohort born between 1956 and 1966 (Leach, 2007). This provides support for the popular view that the 'ski' (spend kids' inheritance) mentality is increasing among recent retirees. Leach also reports a strong interest in travel after retirement among a sample of 50 to 60 year olds in England, which would increase GHG emissions.

4.5 Demographics and innovation potential

The third impact of demographic ageing on GHG emissions is its effect on the supply of skilled human capital to develop and implement technologies to reduce emissions. Skills and capabilities are commonly believed to decline with age, along with an interest in training and upgrading skills (Jones et al, 2010). Consequently, the ageing of the European population could both decrease the quality of the workforce, plus reduce the size of the workforce if older age cohorts are uninterested in working.

Many of these pessimistic assumptions are based on limited data or suffer from strong cohort effects. For example, data on skills, retraining, and workforce participation rates in Europe are influenced by the large cohort of retirees that were born before or during WW II and lived most or all of their working lives in largely 'Fordist' economies with rigid hierarchies and limited control over working conditions. This age cohort has substantially less formal education than younger cohorts. In 2007, 55.3% of Europeans between 60 and 64 years of age had low educational attainment, compared to only 19.4% of Europeans between 25 and 29 years of age (Jones and Hayden, 2009b). Surveys also show that older, poorly educated workers also have little interest in further training. These factors could partly explain why employers view older workers as less productive and resistant to change.

However, the percentage of 45 to 64 year olds that participate in education and training has been increasing over time in the EU-27, from 2.5% in 2000 to 4.7% in 2007. In 2000, the cohort of 45-64 yr olds had been born between 1936 and 1945, whereas the cohort in 2007 was largely born after WW II, between 1943 and 1952. These two cohorts could have experienced different working conditions and expectations. The highest participation in education and training by 45 to 64 year olds in 2007 was in the Nordic countries, with participation rates ranging from 13.6% in Finland to 27% in Sweden. Participation rates were lower in southern Europe, ranging from 0.9% in Portugal to 4.5% in Spain, where Fordist work structures have persisted the longest (Arundel et al, 2007) and where labour participation rates among this cohort are much lower than in the Nordic region (Jones and Hayden, 2009b).

The employment rate of older cohorts within the EU-27 is strongly influenced by educational attainment. In 2007, 61% of 60 year olds with a university degree were employed, compared to 30% of individuals with less than high school (EC Demography, p 101, 2008). As educational attainment levels have been increasing in each younger cohort, workforce participation rates should increase among older age cohorts in the future, even without any policy intervention. Between 2000 and 2007, the percentage of 55-64 year olds in employment increased in Germany (from 37.4% to 51.5%), in the EU-27 from 36.8% to 44.7%, and in the Netherlands from 37.9% to 50.9%. There was little change in Sweden, with employment rates since 2004 at approximately 70%. Perhaps this is the highest level possible for this age group. Of note, the increase in participation rates is largely due to increasing participation by women, in addition to the effect of educational attainment (Jones and Hayden, 2009b). These cohort effects, plus the increasing participation of women in the workforce, suggest that retirement ages will also increase voluntarily.

These results suggest that future cohorts of 55 to 64 year olds will be increasingly open to change, training, and will remain longer in the workforce. This should reduce some of the concerns over pension costs and a declining dependency ratio in Europe.

Another assumption is that inventive capabilities decline with age due to a deterioration in cognitive function. If true, this could reduce the innovative capacity of European R&D and innovation to address climate change. In 2006, 38.1% of all senior scientists and engineers in the EU-27 were aged 45 – 64, with a range from 29.9% in Ireland to 44.8% in Bulgaria. The percentage also increased by 3.3% per year between 2001 and 2006 within the EU-27 (Meri, 2008).

However, based on 2006 data, the share of senior scientists and engineers that are between 45 and 64 years of age has no effect on one measure of scientific output: EPO patent grants per million population in 2005.[47] The results are given in Table 4.1 and control for the effect of public and private R&D expenditures (as a share of GDP). The only variable that has a statistically significant effect on EPO patent grants is business expenditures on R&D.

Table 4.1 Effect of senior S&E share on 2005 EPO patent grants per million population

Variable	*B*	SE	t	Sig.
Share of Senior S&E 45-64 years of age	.212	2.523	.084	.934
Public R&D expenditure share of GDP	-91.149	68.165	-1.337	.193
Business R&D expenditure share of GDP	145.193	21.676	6.698	.000
Constant	2.376	93.581	.025	.980

F = 28.5, p < 0.000, R2 = .774. B for coefficient, SE = Standard Error, t = B/SE, The number of countries = 30, including the EU-27 plus Iceland, Norway and Switzerland. Analysis by the authors.

[47] As the share of senior scientists changes relatively slowly over a short time period, the use of EPO patent data for 2003 should be acceptable. An OLS model is used here, which can result in biases in the size of the coefficient. However, we are primarily interested here in the direction of the effect.

4.6 Conclusions

These trends suggest that older workers and retirees in the future could behave differently from their equivalents in the recent past, requiring a change in assumptions about the lifestyles of retirees, including the types of products that they might purchase, the amount of GHG emissions produced by retirees, the amount that they save, and the interest of older cohorts in remaining in the workforce and continuing to work past current retirement ages.

Currently, the best evidence for Europe suggests that an increase in the age cohort over 65 years of age will slightly increase GHG emissions (after controlling for other effects such as population growth). This is disappointing, since earlier research suggested a large reduction in GHG emissions from demographic ageing. Furthermore, possible changes in consumption patterns among retirees could further increase their GHG emissions compared to other age cohorts, for instance if they increasingly use their leisure time and income for more air travel and long distance holidays. Retirees could also provide a declining source of savings for investment.

There are two positive trends. The first is greater participation in the workforce and delayed retirement, which would partly mitigate an increase in the dependency ratio. A shift towards more training and higher educational attainments of older cohorts will also provide more skilled human capital for both research and to work on zero energy projects. In addition, concerns over a decline in the innovative potential of older cohorts could be overstated. Furthermore, even if older cohorts are less 'cutting edge' and innovative, it may not matter, with an increasingly global research network. On a global scale, there will be no shortage of trained scientists and engineers to conduct research and develop innovations. The share of global R&D conducted in China has increased from approximately 2% in 1996 to 9% in 2007 while India's share increased from 1.4% to 2.1% (OECD, 2010). Europe will continue to have sufficient scientific and engineering capacity to benefit from breakthroughs in green technology that are made abroad, in the same way that Europe has been able for decades to adopt American innovations in computing and software.

The results of this chapter raise some questions on intergenerational equity. Older cohorts have been responsible for high GHG emissions in the past. This historical legacy is partly responsible for the need to decrease the use of fossil fuels in the future. Consequently, younger generations will need to bear more of the economic and social adjustment to a low GHG economy than older generations, even though they were less responsible for the problem. It would therefore be equitable to introduce policies that tax older cohorts at a higher rate for GHG emissions, at the minimum to reduce their per capita emissions to no more than that of younger age cohorts. Alternatively, older age cohorts could pay supplementary taxes to fund R&D into low emission energy technologies.

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5 RESOURCE SCARCITY AND THE CLIMATE CHANGE PROBLEM

5.1 Introduction

Climate change is a physical issue about materials flows. Climate change is caused by the emission of physical substances into the atmosphere including CO_2 and NOx. Greenhouse gas emissions are not only related to the use of fossil fuels but also to the materials we use and whether the materials are recycled. The production of 1 kilo of portland cement generates 1 kilo of CO_2 which can be reduced to half a kilo by replacing lime stone with fly ash. Changes in material inputs are influenced by prices and by government policies. This chapter analyses implications of resource scarcity for climate change and the implications for climate change innovation policy. Resource scarcity has been studied for fossil fuels in the form of prediction of resources and reserves (discovered resources). The economics of fossil fuel resource use are highly important for climate change and the need for action. Scarcity-based price increases for fossil fuels may create demand for fossil-fuel alternatives, but whether or not prices will rise high enough to create the necessary demand is one of the questions that we investigate. This chapter looks into the evolution of material consumption and prices (Section 2), where we will see that material consumption has increased enormously but that resource prices did not show a rising trend in the past 100 hundred years. This may change, at least for some resources. Section 3 investigates resource scarcity issues for fossil fuels, where we will look at estimates for resources and reserves and look at the greenhouse gas emission implications as well as the economics of fossil fuel substitution (natural gas for coal, lpg for petrol etc.). We find that the growing scarcity of conventional oil will give rise to fossil fuel substitution which will dampen price increases for oil and may lead to greater GHG emissions. Section 4 investigates resource scarcity issues of low-carbon technologies: the dependence of low-carbon technologies on scarce materials (such as Lithium and Gallium) and the costs and availability of renewable power sources in different EU Member States. Section 5 investigates the energy security aspects of climate change policy (where we find that climate change policy can help to achieve energy security benefits but that energy security concerns also can act as a barrier). Implications for climate change policy are discussed in section 5.6.

This chapter brings together the findings of many disparate studies due to the lack of good comprehensive studies and to the fact that we are dealing with issues (such as peak oil) that are clouded in uncertainty. It required a significant effort on our part to find relevant studies and to draw conclusions for innovation policy for climate change. In part we had to rely on newspaper articles and grey literature, which are normally beyond the scope of a scientific study. Deeper and more comprehensive analysis is needed on the topic of resource scarcity in how it affects climate change. There are important synergies between sustainable resource management and climate change protection but analysis of these synergies has barely begun. A positive development is that the European Commission has decided to make resource efficiency an important topic for EU policy and that UNEP has established a panel for sustainable resource management.[48]

5.2 Material consumption and prices

Before investigating fossil fuel scarcity and resource aspects of renewables we need to assess material consumption and prices. Resource use in terms of material extraction has increased by a factor of eight between 1900 and 2005 (Fischer-Kowalski and Swilling, 2011, p. 22). In 2005, roughly 59 billion metric tons (Gt) were extracted and used worldwide (Fischer-Kowalski and Swilling, 2011, p. 22). All material products whether food or cement require energy for their creation. Because 80 per cent of energy is sourced via fossil fuels, material processing activities contribute to global warming. In physical terms, fossil fuels account for about 20 per cent of total material extraction in 2005 (Fischer-Kowalski and Swilling, 2011, p. 22).

[48] Information about the aims and activities of the resource panel can be found at http://www.unep.fr/scp/rpanel/

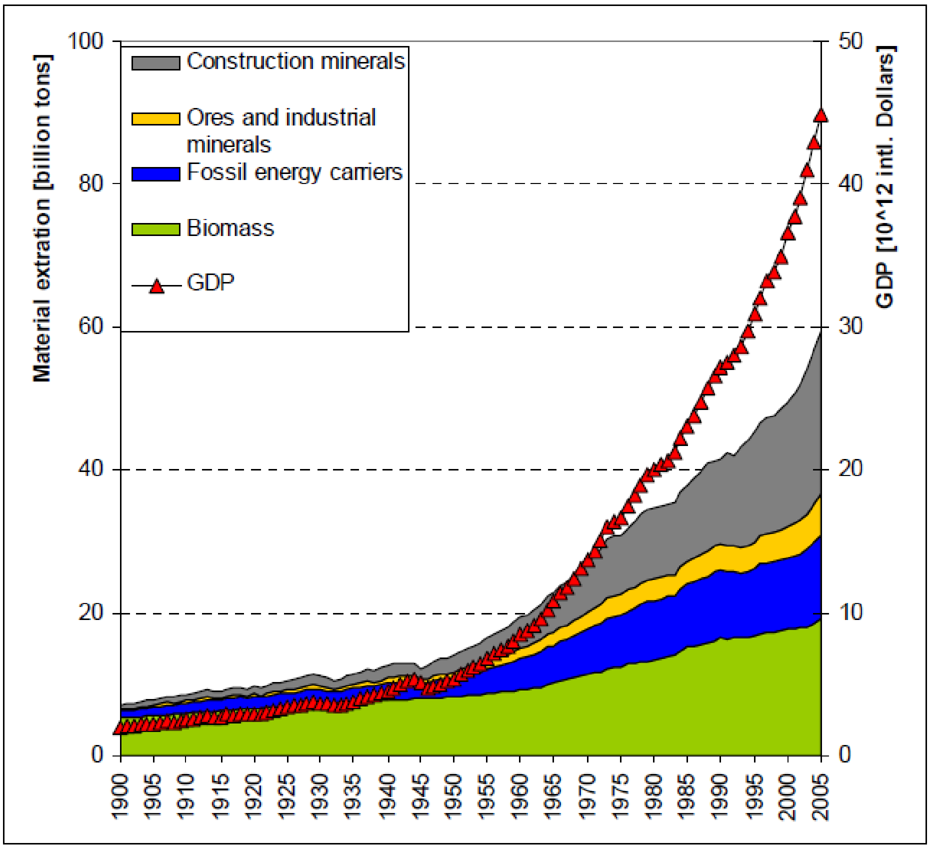

Figure 5.1 **Global material extraction in billion tons, 1900-2005**
Source: Fischer-Kowalski and Swilling (2011, p. 22) based on Krausmann et al (2009)

While global resource use increased by a factor of eight during the 20th centrury, resource use per capita (the metabolic rate) increased by a factor of two in this period (Figure 2.2). The global average metbolic rate has doubled from 4.6 tons in the year 1900 to 8-9 tons at the beginning of the 21st entury (Fischer-Kowalski and Swilling, 2011, p. 23).

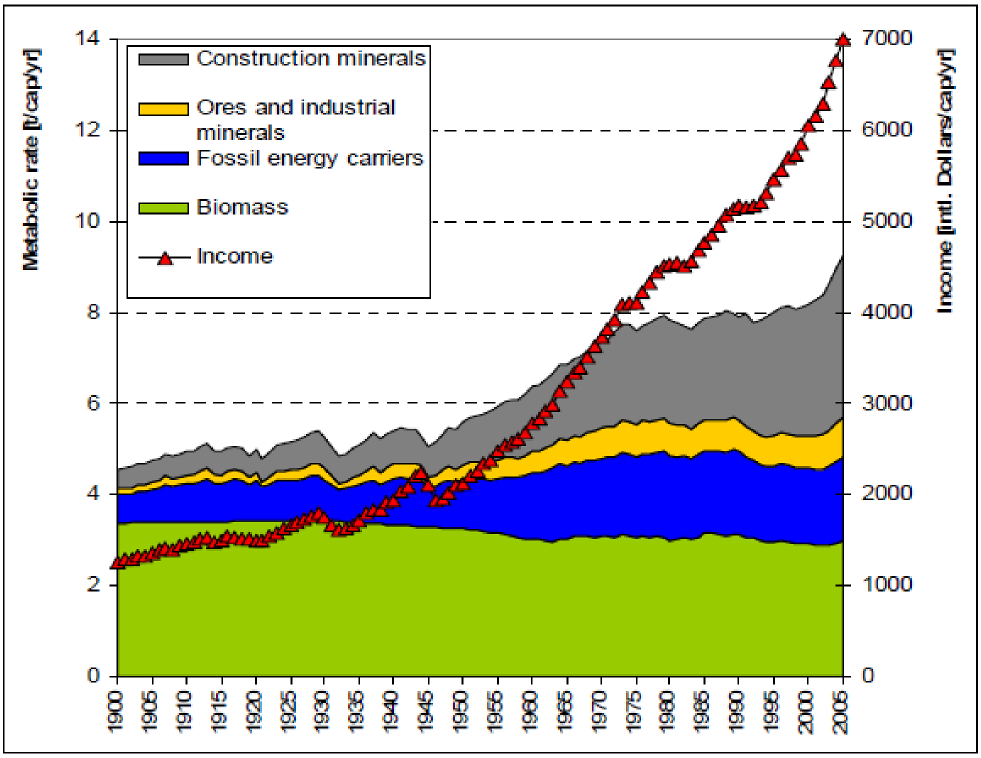

Figure 5.2 **Resources used per capita 1900 – 2005, and income (GDP per capita)**
Source: Fischer-Kowalski and Swilling (2011, p. 24) based on Krausmann et al (2009)

Predictions in the last century that resource constraints would bring about hunger in a world with a growing population (Vogt, 1948; Ehrlich 1967) or a collapse in economic development (Meadows et al., 1972; 2005) proved to be wrong.

Technical change in energy and resource efficiency in manufacturing and transport, energy efficiency of products, substitute materials (for wood and other materials), together with advances in exploration and resource exploitation techniques, helped supply and demand to move in tandem. This was a market driven process. Price peaks were due to temporary supply shortfalls. Counter to the predictions of the Limits to Growth world model (Meadows et al., 1972), inflation-corrected prices for zinc, copper, steel and cement do not show a rising trend over the last 100 years (Figure 5.3). Prices are governed by changes in supply and demand, i.e., they depend on relative scarcity rather than absolute scarcity.

Price indices (1900=100) for zinc, copper, steel and cement 1990-2007

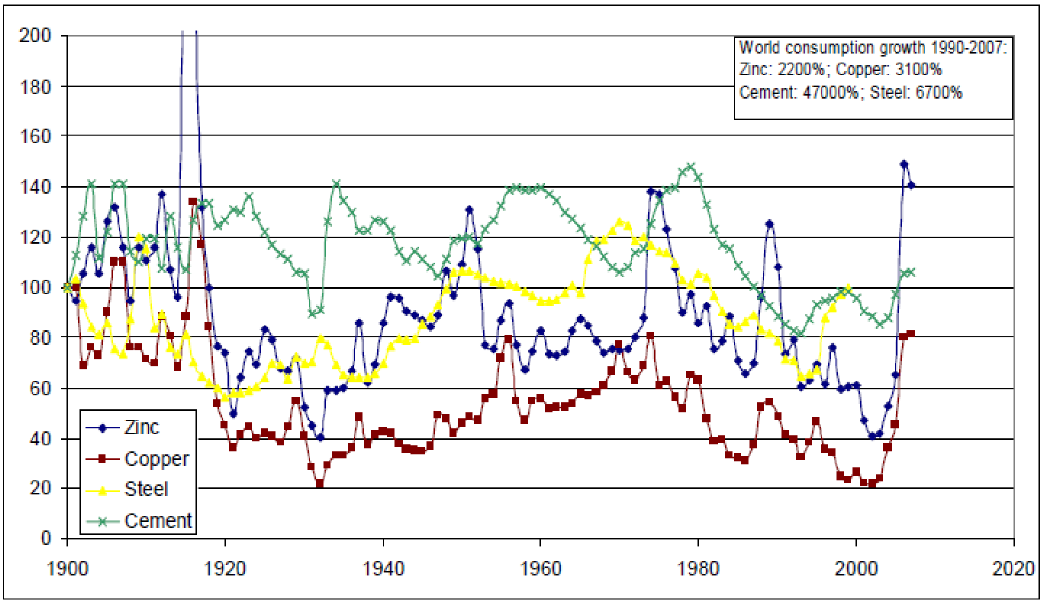

Figure 5.3 **Price indices for zinc, copper, steel and cement, 1990-2007**
Source: US Geological Survey. Price data for steel before 1926 have been standardized on prices of pig iron. From: de Bruyn, et al (2009, p. 71)

With supply and demand being relatively inelastic for materials, a shortfall in supply results in relatively steep price increases. The reason for paying attention to the price developments is to show that it is not at all obvious that prices of depletable resources (and products based on these) must go up. The discovery and exploitation of new resource fields and cost-reducing innovations may help to keep the costs of excavation and processing low, even when lower ore and lower yield fields are exploited. Ultimately the costs of resource exploitation will go up when cheap reserves are exploited, but this may not happen quickly enough to slow the rate of climate change. Renewables may also suffer from scarcity constraints following the exploitation of the lowest cost opportunities. In the next two sections we investigate scarcity issues for fossil fuels and renewables, before highlighting their implications for future GHG emissions.

5.3 Fossil fuels scarcity and climate change

This section looks into the availability and production costs of fossil fuels in the coming decades. Higher costs of fossil fuels will create room for renewables but can we expect the costs of fossil fuels to go up because of scarcity, and if so what kind of price increases are to be expected? Estimates about fossil fuel availability (together with those for nuclear fuels) are given in Table 5.1. The table is based on a distinction between resources and reserves, where reserves are that part of total resources which can be recovered economically using current technology (Gerling, 2005, p. 19).

According to Table 5.1, the greatest resources and reserves are for hard coal. The second most important resource is non-conventional gas (tight gas – gas occurring in coal seams or in coal mines; coal gas; shale gas[49]; gas hydrates – ice-like solids, and aquifer gas). Conventional oil resources are only 1.8% of total resources. Non-conventional oil consists of tar sands, heavy oil and oil shales (shale oils). Reserves for non-conventional oil are con-

[49] Shale gas is gas that is being produced from sedimentary rock containing a significant proportion of solid organic matter that will yield liquid or gaseous hydrocarbons upon heating and distillation (Gerling, 2005, p. 22).

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sidered greater than those for non-conventional gas but advances in hydraulic fracturing and horizontal drilling help to make non-conventional gas economical.

Table 5.1 Reserves, production and resources of non-renewable energy resources at the end of 2003

Type of energy	Reserves		% of total	Production 2003	static lifetime	Resources		% of total
	[EJ]	specific unit			[years]	[EJ]	specific unit	
Hard coal	17,885	763 Gt	50.3	4,421 Mt	173	105,334	4,401 Gt	53.6
Oil, conventional	6,686	160 Gt	18.8	3,549 Mt	45	3,515	82 Gt	1.8
Natural gas, conventional	5,639	178 T.m³	15.9	2,697 G.m³	66	6,886	207 T.m³	3.5
Oil, non-conventional	2,301	66 Gt	6.5	ca. 100 Mt	> 200	10,460	250 Gt	5.3
Lignite	1,602	182 Gt	4.5	928 Mt	225	11,925	1,017 Gt	6.1
Uranium	874	1.7 Mt	2.5	34,997 t	49	8,738	17 Mt	4.4
Thorium	495	1.2 Mt	1.4	n.n.		964	2.4 Mt	0.5
Natural gas, non-conventional	63	2 T.m³	0.2	> 130 G.m³	n.n.	48,633	1,533 T.m³	24.8
Total	**35,545**			**361 EJ**		**196,455**		

Source: Gerling 2005, data from BGR (2004*). n.n. = unknown; EJ = Exajoule = 1018 J*

Figure 5.4 provides an overview of conventional oil discoveries and production of conventional oil in the world. Global oil discoveries have fallen consistently in each decade, but oil production has tended to rise. The discovery rate of conventional oil has been below the rate of oil production since the 1970s.

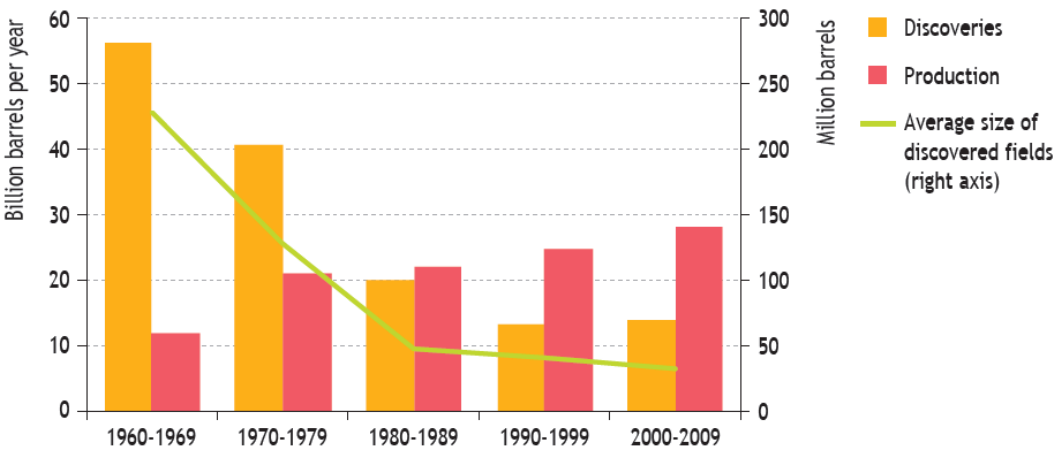

Figure 5.4 Conventional oil discoveries and production worldwide
Source: IEA (2010), p. 217.

Production of conventional oil is expected to peak soon or to have peaked already. Peak oil consists of two phenomena: the *date* at which oil production will peak and the post-*peak decline rate*. On these two topics, we have a range of estimates (Figure 5.5). Conventional oil production may stay at a plateau or fall.

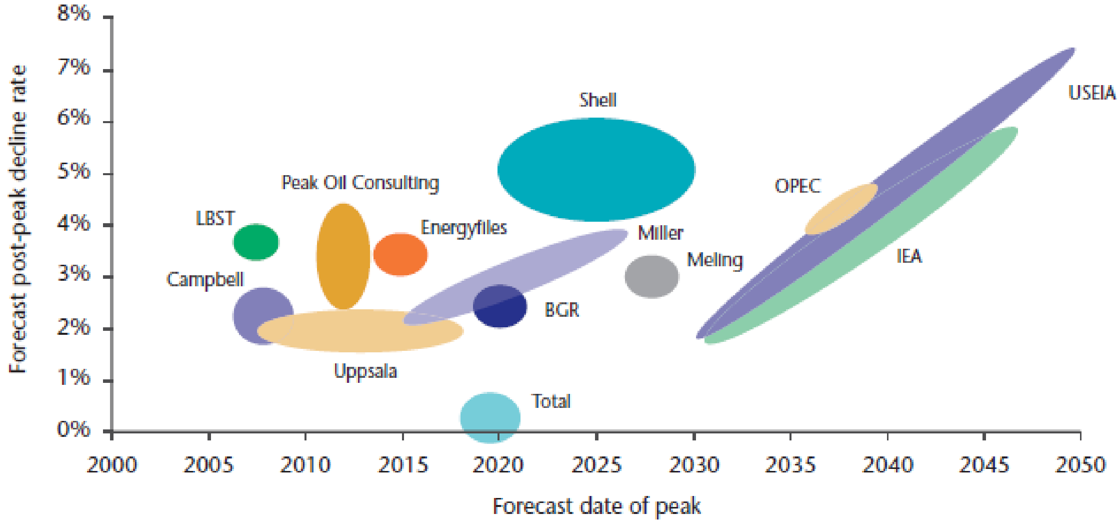

Figure 5.5 **Forecast date of peak and post-peak decline rate for conventional oil production**
Source: WBCSD (2010) based on UKERC (2009)

There are different forecasts for peak oil, based on different methodologies each with their own strengths and weaknesses. The current consensus is that peak oil is near. The chief economist of the IEA believes the production of conventional oil will peak around 2020, about 10 years earlier than is believed by governments.[50] A report by the UKERC on this issue, which scrutinized 500 studies, concluded that peak oil will most likely occur before 2030 and possibly before 2020: "On the basis of current evidence we suggest that a peak of conventional oil production before 2030 appears likely and there is a significant risk of a peak before 2020. Given the lead times required to both develop substitute fuels and improve energy efficiency, this risk needs to be given serious consideration" UKERC (2009, p. X). In the report 'conventional oil' is defined to include crude oil, condensate and natural gas liquids (NGLs) but excludes liquid fuels derived from oil sands, oil shale, coal, natural gas and biomass. Conventional oil is anticipated to provide the bulk of the global supply of liquid fuels in the period to 2030 (UKERC, 2009, p. VI).

Peak Oil does not mean that there will be oil shortages, but simply means that the annual production of *conventional* oil has reached its ceiling. Liquid fuels can be created from non-oil sources (other fossil fuels and biomass) and from non-conventional oil: "a peak in conventional oil production will only be associated with a peak in liquid fuels supply if 'non-conventional' sources are unable to substitute in a sufficiently timely fashion" (UKERC, 2009, p. VI). In its new policy scenario of the 2010 world energy outlook, the IEA foresees a continuing increase in oil production. A large part will come from fields yet to be developed or found (in 2035 new fields are expected account for 50% of oil production) (Figure 5.6).

[50] http://www.independent.co.uk/news/science/warning-oil-supplies-are-running-out-fast-1766585.html

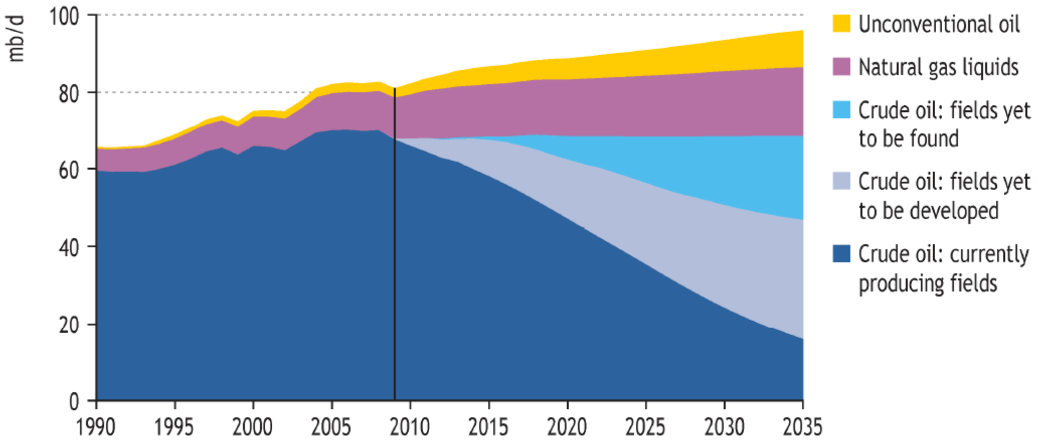

Figure 5.6 **World oil production by type in the New Policies Scenario**
Source: World Energy Outlook 2010 (IEA, 2010)
http://www.worldenergyoutlook.org/docs/weo2010/key_graphs.pdf

Oil companies are investing large sums of money into exploration and exploitation of non-conventional oil. Because of the higher costs of producing non-conventional oil it is expected that the price of oil (and oil-based products such as gasoline/petrol) will rise in coming decades.

The western oil industry is turning its attention to gas. According to an article in the Economist, seven of the eight projects completed by Exxon Mobil in 2009 were in natural gas, and two of the three in 2010 are also gas-related.[51] Royal Dutch Shell expects that by 2012 half of its output will come from gas.[52] The higher costs for oil production, non-access to reserves and future climate change policy are behind the "dash for gas" by Western companies.[53]

In the US there is a lot of activity in shale gas, thanks to advances in horizontal drilling. A Department of Energy study expects the production of shale gas in the US to increase from a total of 1.4 Tcf to 4.8 Tcf by 2020.[54] Unconventional gas production is estimated to increase from 42 percent of total US gas production in 2007 to 64 percent by 2020 (ICF, 2008, p. 24). In its April 2009 report, "Modern Shale Gas Development in the United States: A Primer," the US Department of Energy states that "at the US natural gas production rates for 2007, about 19.3 Tcf, the current recoverable resource estimate provides enough natural gas to supply the US for the next 90 years. Separate estimates of the shale gas resource extend this supply to 116 years" (DOE, 2009, p. ES-1). The estimates about reserves have changed enormously over just a few years. Changes in technology are the main reason behind the changes in expected economic potential: "The rapid advance of drilling and well completion technologies, including hydraulic fracturing, has opened up plays in a number of different basins that were not previously considered to have economic potential" (ICF, 2008, p. 14). The estimates are shrouded in uncertainty: "The volumes calculated for gas-in-place are extremely large, and a small difference in the estimated percentage of gas-in-place that is recoverable has a huge impact on estimates of recoverable resources" (ICF, 2008, p. 14).[55]

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[51] http://www.economist.com/node/16488892?story_id=16488892

[52] http://www.economist.com/node/16488892?story_id=16488892

[53] According to the Economist, "a $30-a-tonne carbon tax would make gas—which is about half as polluting as coal when burnt—the preferred fuel for new power stations". http://www.economist.com/node/16488892?story_id=16488892

[54] DOE (2009) quoted in http://www.api.org/policy/exploration/hydraulicfracturing/shale_gas.cfm. Tcf stands for trillion cubic feet.

[55] The conclusion is based on the November 2008 report of the Interstate Natural Gas Association of America (INGAA) "Availability, Economics and Production Potential of North American Unconventional Natural Gas Supplies," The INGAA report stated that to achieve the forecast results, industry must have land access for drilling, a reasonable permitting process and adequate prices and demand for natural gas. http://www.api.org/policy/exploration/hydraulicfracturing/shale_gas.cfm

In Europe there is no actual shale gas exploitation but exploration is increasing (Figure 5.7) Europe's unconventional gas reserves may total 1,200 trillion cubic feet, according to Shell, about five times the continent's proven gas reserves, [56] but drilling shale gas fields in Europe profitably may prove harder than in the U.S. In Poland, shale deposits are drawing interest from companies including Exxon Mobil Corp., ConocoPhillips and Chevron Corp., according to the Polish Geological Institute.[57] Drilling projects are being undertaken to discover whether the gas is accessible.

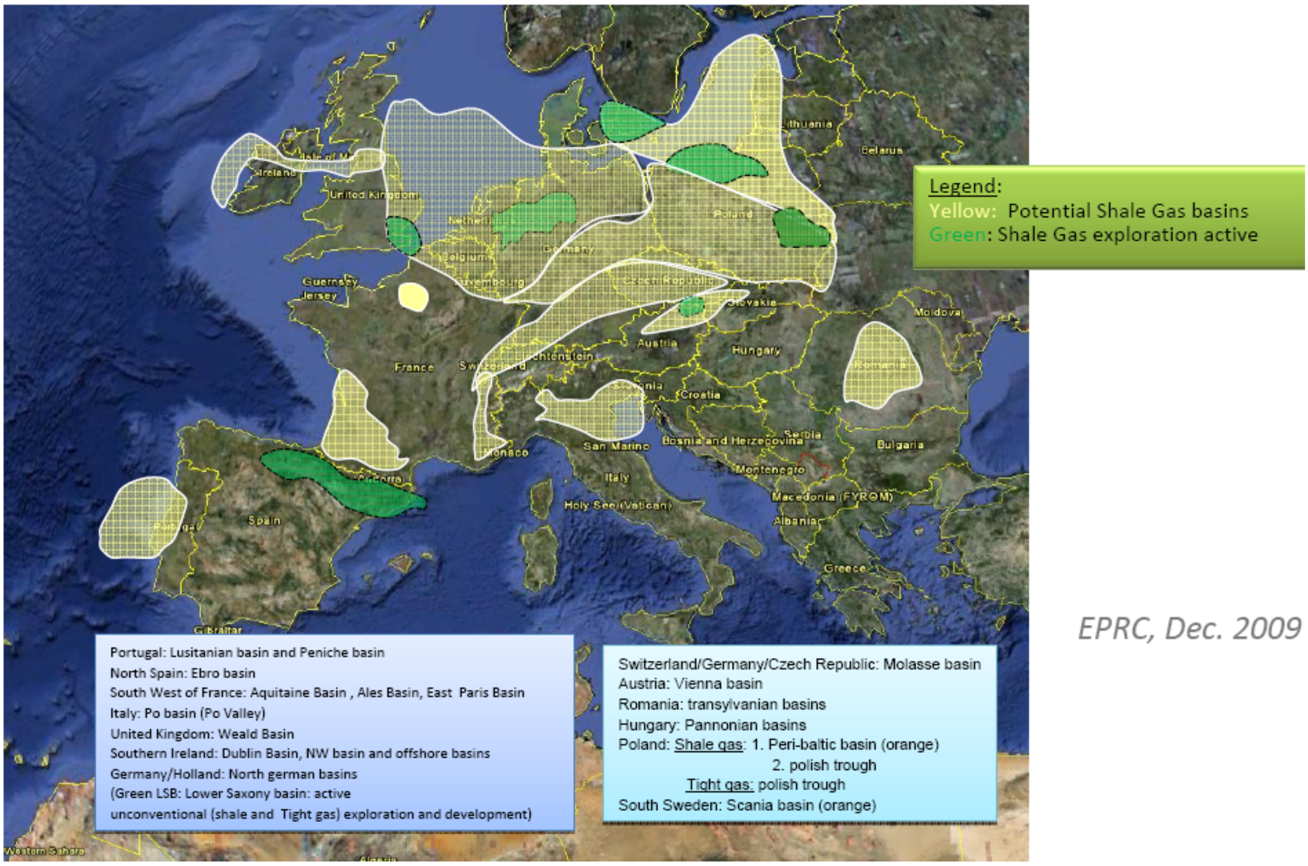

Figure 5.7 **Shale gas depositories in Europe**
Source: http://www.europeanenergyreview.eu/data/docs/Viewpoints/ppt0000002.pdf

Gas may be a game changer, and yet it may not. Beyond the economic risks there are also health and environmental risks to take into account. The US Environmental Protection Agency (EPA) is currently investigating the potential impact of shale gas development on drinking water and public health. The discovery of such risks may have a major impact not only in the US but across the shale gas industry.[58]

There is also the possibility of producing transport fuels from coal and gas. During the second world war Germany used the Fischer-Tropsch-synthesis to produce synfuels out of gasified coal and South Africa did the same because of oil boycots. Liquid fuels can also be made from natural gas and this is increasingly done. In 2008, Shell signed on to build a $5 billion Gas-to-Liquid Plant in Qatar.59 GTL technology converts liquefied natural gas (LNG) into fuels that can be used in normal diesel engines and can also be blended into conventional diesel fuel. CO_2

[56] http://www.businessweek.com/news/2010-04-08/poland-calls-on-europe-to-emulate-u-s-shale-gas-development.html
[57] http://www.businessweek.com/news/2010-04-08/poland-calls-on-europe-to-emulate-u-s-shale-gas-development.html
[58] http://www.riskwatchdog.com/2010/09/29/shale-gas-a-global-energy-game-changer/
[59] http://www.siteselection.com/ssinsider/snapshot/sf040202.htm

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emissions are estimated to be 25% below those from diesel, NOx and volatile organic hydrocarbon emissions are less than half of those from diesel but methane emissions (another GHG) are higher (EPA, 2002). The GTL plant agreement came shortly after ExxonMobil signed a $12-billion LNG pact with Qatar. Beginning in 2008, Qatar will annually export 15.6 million tons (14.04 metric tons) of LNG to ExxonMobil for 25 years.[60] A GTL system, compared to a crude oil refinery system, produces a lower total amount of carbon dioxide emissions when a carbon dioxide capture and sequestration unit is used. Total emissions for a GTL system with CCS are 78 kg carbon dioxide per GJ, compared to 83 for a crude oil refinery.[61]

For now GTL is a niche strategy for remote gas (for which the building of a piping infrastructure to gas users is too expensive) and as an alternative to gas flaring. High oil prices and carbon taxes may lead oil companies to shift to GTL but they may be disinclined to do so when this means that they have to close one or more refineries.

The industry's view is that the era of cheap oil is over, leading the industry into non-conventional oil and natural gas projects. From a climate change point of view the shift to non-conventional oil will add to GHG emissions but we lack precise estimates of how much. A shift to natural gas for power production and to natural gas-based fuels in transport will bring climate benefits compared to the use of conventional oil.[62] The price of oil is expected to rise, given predicted demand and supply possibilities. In the New Policies Scenario - of full implementation of climate change commitments made by nations - the IEA expects the crude oil price to increase from just over $60 in 2009 to $113 per barrel (in year-2009 dollars) in 2035. Relatively modest price increases are thus foreseen for oil. Oil demand is expected to grow steadily, from 84 million barrels per day in 2009 to 99 million barrels per day by 2035 (IEA, 2010). Within the IEA New Policies Scenario oil remains the leading fuel in the energy mix by 2035, followed by coal. Of the three fossil fuels, gas consumption is envisioned to grow the most, reaching a share close to that of coal. The share of modern renewable energy sources, including sustainable hydro, wind, solar, geothermal, modern biomass and marine energy, in global primary energy use is expected to triple between 2008 and 2035, reaching a share of 14% (IEA, 2010).

Resource scarcity of fossil fuels is helping renewables but within the coming 25 years relatively small price increases are expected (Figure 5.8). Moreover, renewables have their own resource problems, as the next section will show.

[60] http://www.siteselection.com/ssinsider/snapshot/sf040202.htm

[61] http://students.chem.tue.nl/ifp23/interim_report/gtl.html

[62] Per unit of energy, natural gas produces approximately 48% less CO_2. But Ramanathan and Feng (2008) note that natural gas produces significantly fewer aerosols such as sulfates compared to oil and coal. As these aerosols block atmospheric warming, the short-term effect of natural gas on warming could be stronger than the effect of oil and coal.

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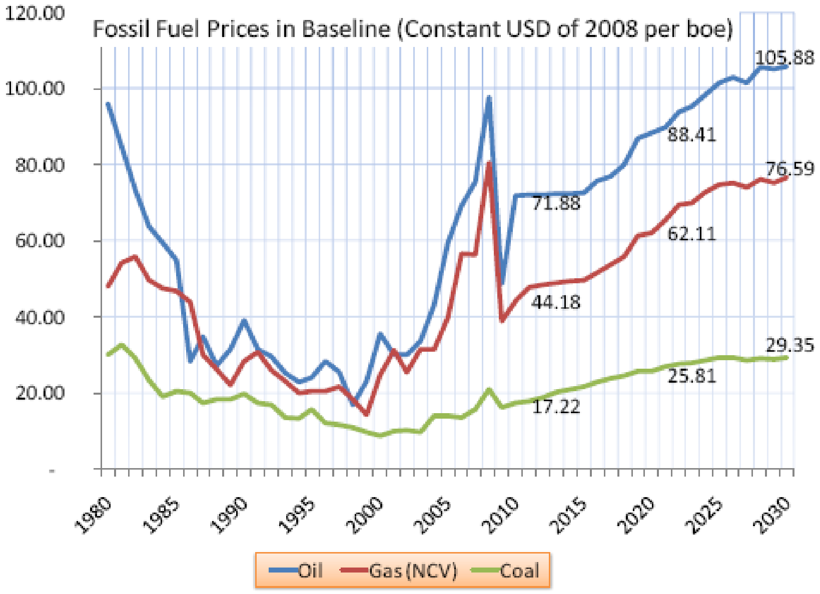

Figure 5.8 **World fossil fuel prices**[63]
Source: EC (2010, p. 16).

5.4 Resource scarcity issues for renewables

Renewables also suffer from resource constraints, in the form of critical materials being used for the production of technology components (of solar PV, wind turbines, automotive batteries), availability of land (for biomass) and availability of water (for hydropower). This section will look into these rescource constraints.

5.4.1 The dependence of renewables on scarce materials

A resource issue which so far has not received much attention in the media and popular mind is the dependence of several renewables on scarce materials. Lithium-ion batteries for cars use cobalt, PV panels use indium and gallium, wind turbines use neodymium, fuel cells require platinum, and micro-capacitors for electric cars require niobium and tantalum– all 'critical materials' whose availability is limited as one can see in Table 5.2.

[63] The price predictions for the EU27 stem from the PROMETHEUS stochastic world energy model that derives price trajectories for oil, gas and coal under a conventional wisdom view of the development of the world energy system (EC, 2010b, p. 16). The prices are corrected for inflation. The 106 USD price for oil in 2030 is below the estimate of the EIA International Energy Outlook 2009 which assumes 134 $/barrel in 2008 prices (EC, 2010b, p. 16).

Table 5.2 Raw materials for emerging technologies

Raw material	Emerging technologies (selected)
Antimony	ATO, micro capacitors
Cobalt	Lithium-ion batteries, synthetic fuels
Gallium	Thin layer photovoltaics, IC, WLED
Germanium	Fibre optic cable, IR optical technologies
Indium	Displays, thin layer photovoltaics
Platinum (PGM)	Fuel cells, catalysts
Palladium (PGM)	Catalysts, seawater desalination
Niobium	Micro capacitors, ferroalloys
Neodymium (rare earth)	Permanent magnets, laser technology
Tantalum	Micro capacitors, medical technology

Source: European Commission (2010) Report of the Ad-hoc Working Group on defining critical raw materials, Brussels, p. 8.

Table 5.3 Supply of raw materials and demand from emerging technologies

Raw material	Production 2006 (t)	Demand from emerging technologies 2006 (t)	Demand from emerging technologies 2030 (t)	Indicator[1] 2006	Indicator[1] 2030
Gallium	152	28	603	0,18	3,97
Indium	581	234	1.911	0,40	3,29
Germanium	100	28	220	0,28	2,20
Neodymium (rare earth)	16.800	4.000	27.900	0,23	1,66
Platinum (PGM)	255	very small	345	0	1,35
Tantalum	1.384	551	1.410	0,40	1,02
Silver	19.051	5.342	15.823	0,28	0,83
Cobalt	62.279	12.820	26.860	0,21	0,43
Palladium (PGM)	267	23	77	0,09	0,29
Titanium	7.211.000 [2]	15.397	58.148	0,08	0,29
Copper	15.093.000	1.410.000	3.696.070	0,09	0,24

Source: European Commission (2010) Report of the Ad-hoc Working Group on defining critical raw materials, Brussels, p. 7

[1] The indicator measures the share of the demand resulting from driving emerging technologies in total today's demand of each raw material in 2006 and 2030

[2] Ore concentrate

By 2030 predicted demand from renewable-relevant emerging technologies for gallium, indium, neodymium, platinum and tantalum exceeds current production levels, which would therefore have to go up but whose supply is limited. Several materials experienced price peaks because of demand exceeding supply. One example is indium, a metal used in thin-film CIGS solar cells, whose price increased from 100 USD in 2002 to 800 USD in 2006[64]. The reason for the increase was rapidly growing demand for LCD flat screens using indium. Because indium is mined as a by-product of zinc, supply could not adjust quickly, which led to the price increases.

Competition from different industries may create temporary price peaks. Companies as well as public research institutes are searching for more abundant alternatives to indium tin oxide. Much is expected from organic technology because the material is abundant and cheap and allows for the production of flexible solar cells (foils).

[64] See http://geology.com/articles/indium.shtml (based on data from USGS Mineral Commodity Summaries)

As with fossil fuels there are substitution possibilities for critical materials, some of which may require public research support. Recycling is another strategy for dealing with resource scarcity and this makes a good deal of sense from a climate change point of view because material processing is often energy intensive. According to a recent study by Prognos (2008), waste management can achieve an additional reduction of between 134 and 234 Mton CO2 or 19-31 per cent of the CO2 reduction target for the EU in 2020. The reduction in CO2 is achieved through increased recycling and energy recovery of materials (including biodegradable waste from municipal solid waste). To achieve these CO2 reductions the study proposes higher recycling targets and the use of energy recovery targets for municipal solid waste, and construction and demolition waste.

Rare materials are often mined together with bulk materials. The exhaustion of regular materials such as copper and zinc may make the production of rare materials more costly and in some cases prohibitively costly. For the short term this is not expected to be a major issue, given that most materials can be mined for 40 years or more (Figure 5.9) and because of substitution possibilities.

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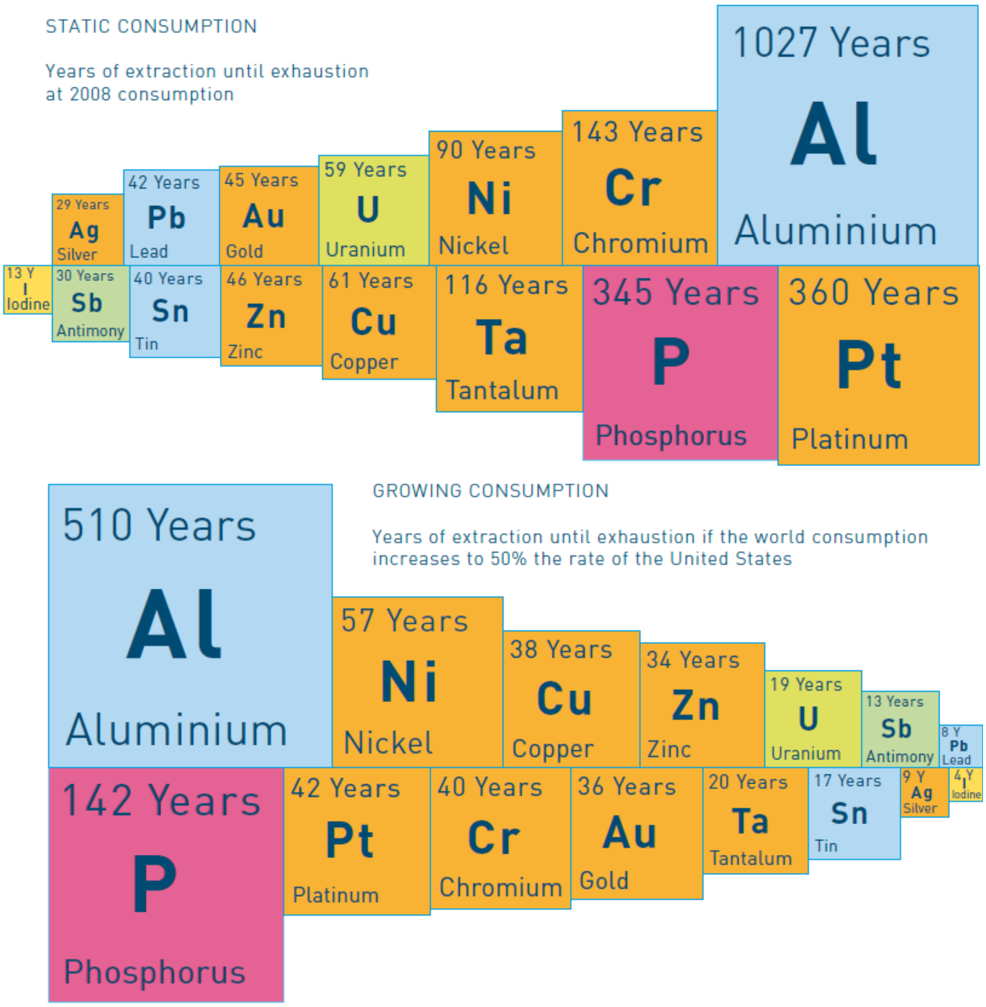

Figure 5.9 **Estimated years of extractions by static and growing consumption**
Source: HCCS (2010, p. 24)

All resources have international security implications related to access. Of special concern presently are rare earth metals used for renewables energy technologies. Many of the rare earth metals are found in China which applies export quotas for strategic reasons. This could be of importance from a climate change point of view.

Table 5.4 Strategic minerals from China

MINERAL	SHARE[50]	EXPORT QUOTA (2010)	MAIN APPLICATIONS
DYSPROSIUM	99%	Full export ban	Permanent magnet (electrical vehicles; windturbines)
LANTHANUM	95%	ca. 9.000 tonnes[51]	NiMH battery (electrical vehicles)
NEODYMIUM	95%	ca. 5.000 tonnes[52]	Permanent magnet (electrical vehicles; windturbines)
ANTIMONY	87%	57.500 tonnes	Semiconductors, solder
TUNGSTEN	84%	14.300 tonnes	High-performance steel; industrial cutting tools
GALLIUM	83%	-	Semiconductor (solar energy; LEDs; defense)
GERMANIUM	79%	-	Semiconductor (solar energy; fiber optics; infrared)
INDIUM	60%	233 tonnes	Semiconductor (LCD displays; solar energy; LEDs)
MAGNESIUM	48%[53]	1.330k. tonnes	Light-weight alloys (e.g. car bodies, airplanes)
TIN	40%	21.000 tonnes	Solder, tinplate (e.g. conservatives)
VANADIUM	38%	-	High-performance steel (e.g. jet engines)
MOLYBDENUM	28%	25.500 tonnes	High-performance steel (e.g. rocket engines)

Source: HCCS (2010, p. 86)

The Chinese government plans a further reduction for 2011 of up to 30 percent in its quotas for exports of rare earth minerals, according to the official newspaper China Daily, "in an attempt to conserve dwindling reserves of the materials". The Chinese policy is viewed as being in conflict with World Trade Organization rules that forbid countries from imposing restrictions on exports of materials so as to force importing countries to buy finished products instead of importing the materials, although the rules allow export restrictions for the purpose of conserving natural resources.[65]

What is less well known is that the US, Canada and Australia have their own reserves of rare earth metals. For example the Mountain Pass site in the US has "proven reserves of more than 30,000,000 tons of ore when measured using a lower cut-off grade of 7.6%". At today's American demand of 20,000 metric tons a year, Mountain Pass is said to be able to be able to provide "light" rare earths, lanthanum through samarium, in sufficient quantities to supply current demand for 150 years.66 From 1984 to 2002 Mountain Pass was producing rare earth metals, but the

[65] http://www.nytimes.com/2010/10/19/business/global/19mineral.html

[66]http://www.ensec.org/index.php?option=com_content&view=article&id=228:the-battle-over-rare-earth-metals&catid=102:issuecontent-&Itemid=355

production became uneconomical as a result of cheap (underpriced) Chinese materials. When prices go up, exploitation can be expected to be resumed. Higher prices will also promote a search for rare earth minerals in other parts of the world and the search for substitutes.

5.4.2 Cost and resource limits to renewable energy

A far more important constraint to low-carbon energy technologies than the (future) scarcity of critical materials is the costs of producing renewable energy in different nations. Nations differ in their potential for renewable energy technically and economically. In the OPTRES project for the European Commission the potential for renewable energy is assessed for 25 EU Member States based on a dynamic cost-resource analysis. The study calculates six types of potential. There is a theoretical potential based on general physical parameters linked to winds and solar radiation, a technical potential based on efficiencies of conversion technologies and land available for energy crops and placing wind turbines, a maximum realistic potential in view of deployment barriers linked to economic costs, supply constraints and time being needed for planning permission and so on, and an economic potential based on costs and endogenous technological learning. The maximum realistic potential in 2020 is called the mid-term potential. Subtracting the actual potential from the maximum time path for penetration gives the additional realisable potential (Figure 5.10).

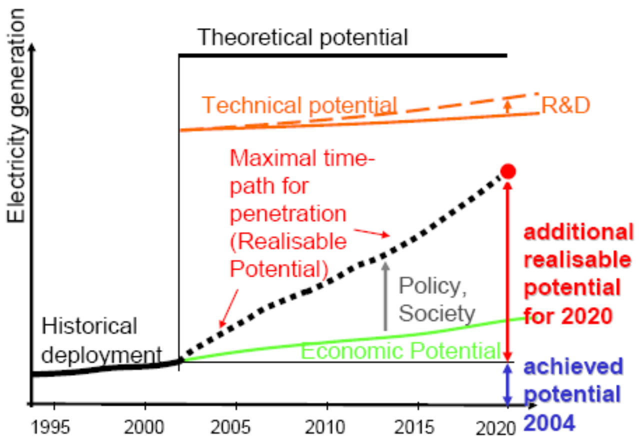

Figure 5.10 **Overview of potential terms for renewable electricity**
Source: Report **(D4)** of the IEE project OPTRES: Assessment and optimisation of renewable support schemes in the European electricity market, p. 15

An overview of the achieved levels and mid-term potential levels for renewable electricity for EU-15 and EU-10 countries is given in Figure 5.11 and 5.12 (left). A breakdown of the potential according to the renewable energy category is given on the right hand side. Large countries have greater potentials (in absolute terms) than small countries. The greatest additional potential is for biomass and wind power. Of the EU-10 countries Poland has the greatest potential for renewable energy sources for electricity (RES-E) thanks to available land for biomass. The potential for additional hydro-electricity is small because hydro power is already well exploited. By contrast the potential for tide and wave power is hardly exploited. For the EU-15 the achieved potential for RES-E equals 441 TWh. For the EU-10, it is 19 TWh. The additional realisable potential up to 2020 is estimated at 1056 TWh for the EU-15 and estimated at 118.7 TWh for the EU-10. This amounts to 38% and 36.1% of current gross electricity consumption (Resch et al., 2006, p. 17-18).

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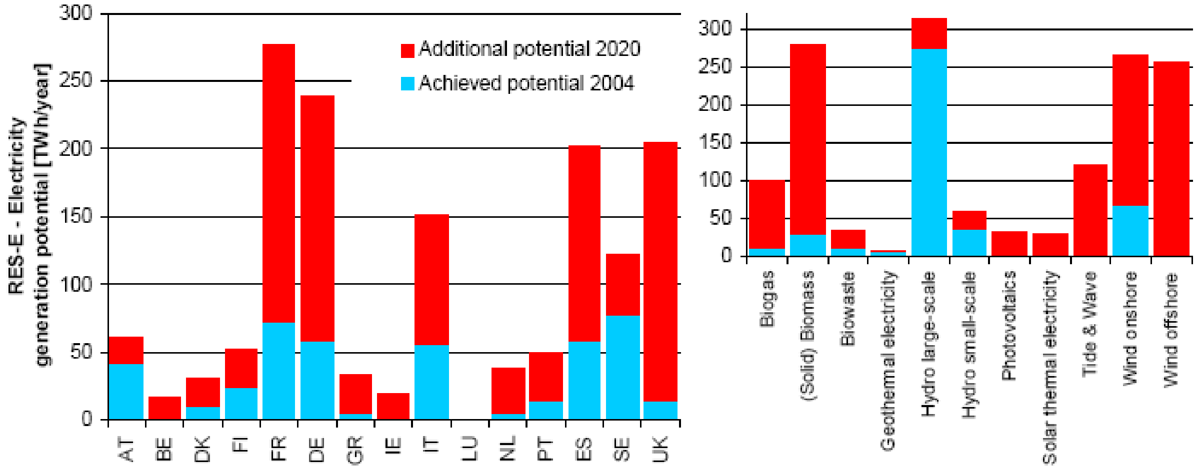

Figure 5.11 **Achieved (2004) and additional mid-term potential 2020 for electricity from RES in EU-15 countries by country (left) and by RES-E category (right)**

Source: Report (D4) of the IEE project OPTRES: Assessment and optimisation of renewable support schemes in the European electricity market, p. 18

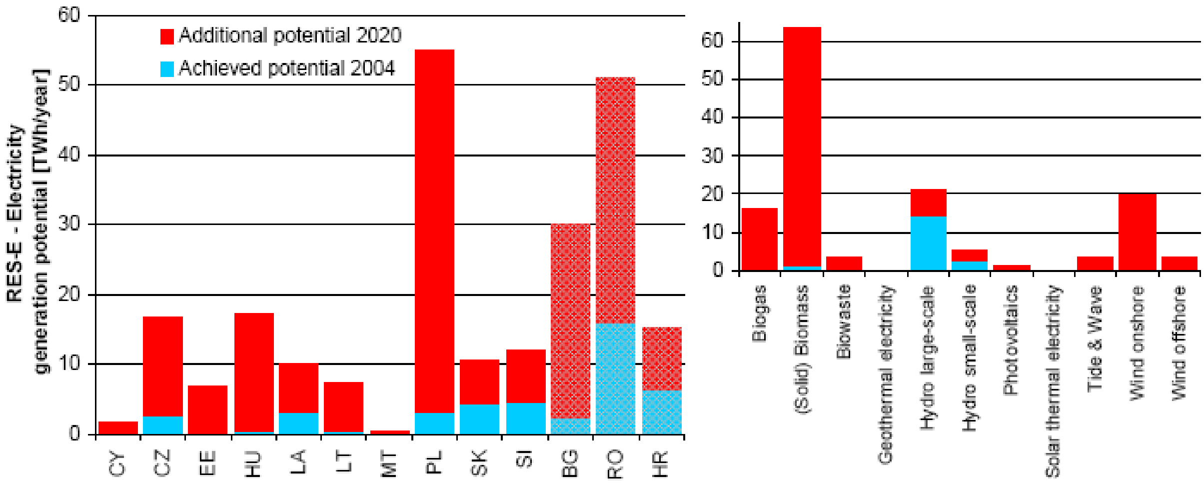

Figure 5.12 **Achieved (2004) and additional mid-term potential 2020 for electricity from RES in EU-10 countries & BU, RO, HR by country and by RES-E category**

Source: Report (D4) of the IEE project OPTRES: Assessment and optimisation of renewable support schemes in the European electricity market, p. 18

Figure 5.13 relates derived potentials to gross electricity demand. It depicts the total realisable mid-term potentials (up to 2020) for RES-E as share of gross electricity demand in 2004 and 2020 for all EU-25 countries as well as the EU-25 in total. Expected demand plays an important role. If the demand increases as expected under 'business as usual' conditions, only 41% of gross consumption can be covered by RES-E options. If a demand stabilisation can be achieved, RES-E may contribute to meet about 53% of total demand under a full exploitation scenario. The greatest potential is for Austria, Portugal and Latvia. If energy demand does not increase, those countries will be able to meet their entire demand with renewables according to the Green-X model. Luxemburg, Malta, the Czech Republic, Slovakia, Poland and the Netherlands have a low potential. In those countries renewable energy from domestic sources cannot provide for more than 25% of the energy if energy demand continues to grow.

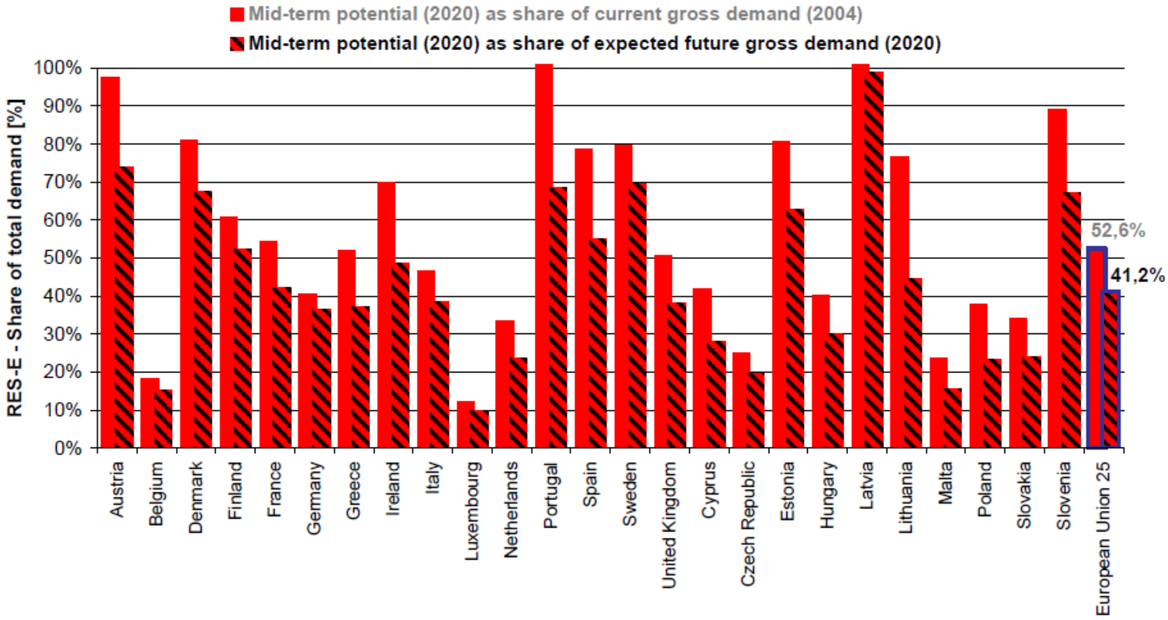

Figure 5.13 **Total realisable mid-term potentials (2020) for RES-E in EU-25 countries as share of gross electricity demand (2004 & 2020)**
Source: Report (D4) of the IEE project OPTRES: Assessment and optimisation of renewable support schemes in the European electricity market, p. 20.

A later assessment for *final energy* (instead of electricity) puts the maximum RES-share for the EU27 at 27.5% based on expected demand (and at 28.5% based on 2005 demand) (Ecofys, 2011). The largest contributor to RES is the heat sector, with 14.2%, followed by the electricity sector, 11.3% (Figure 5.14). In these two sectors around 35-40% of the potential has been achieved in 2005. The transport sector has the lowest expected potential for renewables. Only 3.1% of final energy can be met by domestic biofuels.

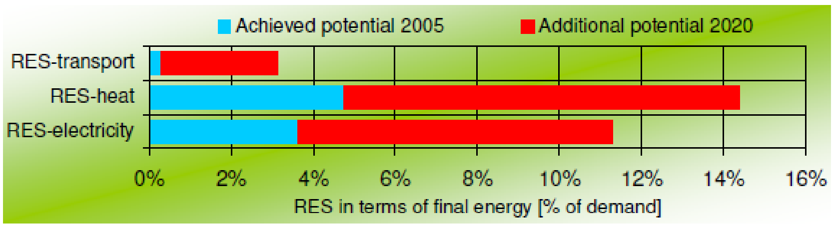

Figure 5.14 **Sectoral breakdown of the achieved (2005) and additional 2020 potential for RES in terms of final energy at EU27 level, as share on gross final energy demand**
Source: Ecofys (2011, p. 23)

The calculations are only indicative for the potential for renewables and should not to be viewed as predictions. Technical and societal constraints are considered only for onshore wind energy. The estimates for potential are based on a techno-economic analysis, which draws on learning curves. There is rapid growth (thanks to active government support). Between 2005 and 201, renewable energy consumption doubled: from 102 Mtoe in 2005 to 217 Mtoe in 2010 (gross final energy consumption). In 2009, investment in renewable energy constituted 62% of energy generating investments.[67]

[67] COM(2011) 31 Final, p. 4.

The potential for renewable energy in Europe is also investigated in the study by DLR (2006). The focus of the study is on concentrated solar power. Drawing on various studies, the DLR arrives at the following outlook for electricity supply in Europe.

Table 5.5 Electricity demand in 2050 in European countries compared to the total economic renewable electricity potential

Unit: TWh/y	Demand 2050	Total Ren. Econ. Pot.	Coverage in 2050
Austria	49,0	96,6	197%
Cyprus	5,0	27,9	558%
Denmark	51,1	65,1	127%
Finland	76,4	104,3	137%
France	426,0	329,7	77%
Czech Republic	51,7	29,9	58%
Belgium	67,0	23,2	35%
Ireland	34,0	67,6	199%
Luxembourg	10,9	2,2	20%
Netherlands	116,0	56,3	48%
Sweden	153,7	240,9	157%
Switzerland	39,4	50,0	127%
United Kingdom	451,2	450,8	100%
Poland	190,9	129,9	68%
Bulgaria	26,5	31,4	119%
Slowac Republic	29,5	22,5	76%
Slowenia	9,3	16,0	171%
Germany	548,8	433,6	79%
Hungary	43,9	70,5	161%
Greece	62,1	89,5	144%
Italy	310,6	237,2	76%
Malta	2,4	2,3	95%
Portugal	62,0	220,1	355%
Spain	320,1	1513,1	473%
Turkey	494,1	723,4	146%
Macedonia	11,5	7,3	63%
Croatia	20,3	24,4	120%
Romania	96,1	69,8	73%
Serbia & Montenegro	49,2	48,8	99%
Bosnia-Herzegowina	17,8	29,2	164%
Iceland	6,6	233,8	3567%
Norway	112,0	290,7	259%
Total	3945	5738	145%

Red indicates countries whose domestic renewable electricity power is small than expected demand.
Green indicates countries with excess economic potential.
Source: DLR (2006, p. 59)

According to the DLR study, there is enough potential in the analysed countries to meet the entire electricity demand, but it notes that about 30% of the analysed countries show considerable deficits, including countries such as Germany and France. One quarter of the European potential stems from one single source, in one country: concentrated solar power in Spain (DLR, 2006, p. 59).

For a number of reasons the study finds it unlikely that the available potentials will cover 100% the total European electricity demand:

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1. “About 60 % of the economic renewable electricity potential in Europe is represented by wind and solar energy, both highly fluctuating resources that cannot deliver power on demand.”
2. “Most renewables except hydropower and wind energy are not yet visible in the European energy mix today. To grow to considerable shares requires time, defined by the growth rates of the respective industrial production capacities. Although growing quickly today, with spectacular rates of 25-60 %/y for wind and PV, a considerable share of renewables will not become visible in the total energy mix before 2020. To cover the power demand until renewables can really take over the core of electricity supply, (…) new fossil fuel based power capacities will have to be installed from here to 2050. Once installed, those capacities will not be decommissioned before their economic lifetime is over, thus still blocking the respective market segment in 2050 and afterwards”
3. “The economic learning curves of renewable energy technologies will require a certain time span to come to a competitive level. (…) Public concern is increasingly pushing wind power to offshore regions, and hydropower plants are subject to increasing environmental constraints, creating additional challenges for each technology that still must be overcome and will take time to be solved.”
4. “Public support of renewables must balance the expectations of private investors with adequate incentives for cost reduction to achieve an optimal allocation of funds. Therefore, only a support exactly fitting to the real cost level of each technology and subsequently reduced over time will induce optimal learning and development. Neither scarce nor excessive funding would be helpful to achieve that goal.”

(From DLR, 2006, p. 60)

We think that these are valid points, which suggest that it is unrealistic to expect renewables to be able to meet power demand entirely by 2050. All technologies face constraints. Relatively economical technologies such as on-shore wind and hydropower face siting problems, those that are less economical face public support constraints. According to a study by the Dutch Task Force Wind energy at sea, total production costs per MWh for offshore windpower vary from €173 in Belgium to €180 in the Netherlands and Germany and €182 in the UK (i.e. from 17.3 to 18.2 eurocents per kWh). The task force estimates at 150 billion euro the investment costs of European plans to put in place 40 GW of offshore wind power in the North Sea and Baltic Sea (Task force Wind Energie op Zee, 2010). It is unclear what level of government support will be needed to make this possible. Pieter Tavenier, Director Offshore of Eneco (the third largest Dutch utility, owner of a 120 MW offshore windpark off the Dutch coast), estimates that 40,000 MW in 2020 requires €100 billion in government support.[68]

Whatever the exact costs, it is unrealistic to expect European governments to meet these very high costs. The new Dutch government has already announced plans to cut support for wind power. Costs therefore have to be re-covered via wider diffusion. For this an industry-wide effort is said to be needed, in which manufacturers share knowledge and seek benefits from standardization and economies of scale. Costs may also be brought down through cheaper components and cheaper operation and maintenance.[69] It is unclear what kind of cost reductions can be achieved, and how these will compare to those of other low-carbon options.

There is a growing interest in nuclear power as a low-carbon technology. But as for CCS, nuclear power plants face constraints in terms of societal acceptance, planning permission, high investment costs and capacity constraints on the part of suppliers. Nuclear power stations cannot be built quickly and are therefore not a short-term option. In the Netherlands planning procedures have been launched for two nuclear plants. The stations could be operational by 2018 and 2019 respectively according to the companies who submitted the plans. In the past decade capital costs for building nuclear plants have been increasing. According to Lovins and Sheikh (2008, p. 7-8) “the dominant cause for the rising costs is severe manufacturing bottlenecks and scarcities of critical engineering, construction, and management skills that have decayed during the industry’s long order lull”.

The costs of nuclear power are a contentious issue, much more than the costs of other energy technologies. According to Lovins et al (2009) nuclear power is more expensive than other options, and will require state support.

[68] http://www.offshorewind.biz/2010/06/02/offshore-wind-in-its-hard-times/.

[69] http://www.offshorewind.biz/2010/06/02/offshore-wind-in-its-hard-times/

Nuclear power is more expensive than power from coal plants. The cost of new delivered electricity is lowest for co-generation, where the heat is re-used (Figure 5.14). Cogeneration helps to extract more energy from fossil fuels (Ayres and Ayres 2009) and constitutes a low-cost trajectory for climate mitigation, which should be more widely exploited. This would require changes in regulation and removal of other institutional barriers.

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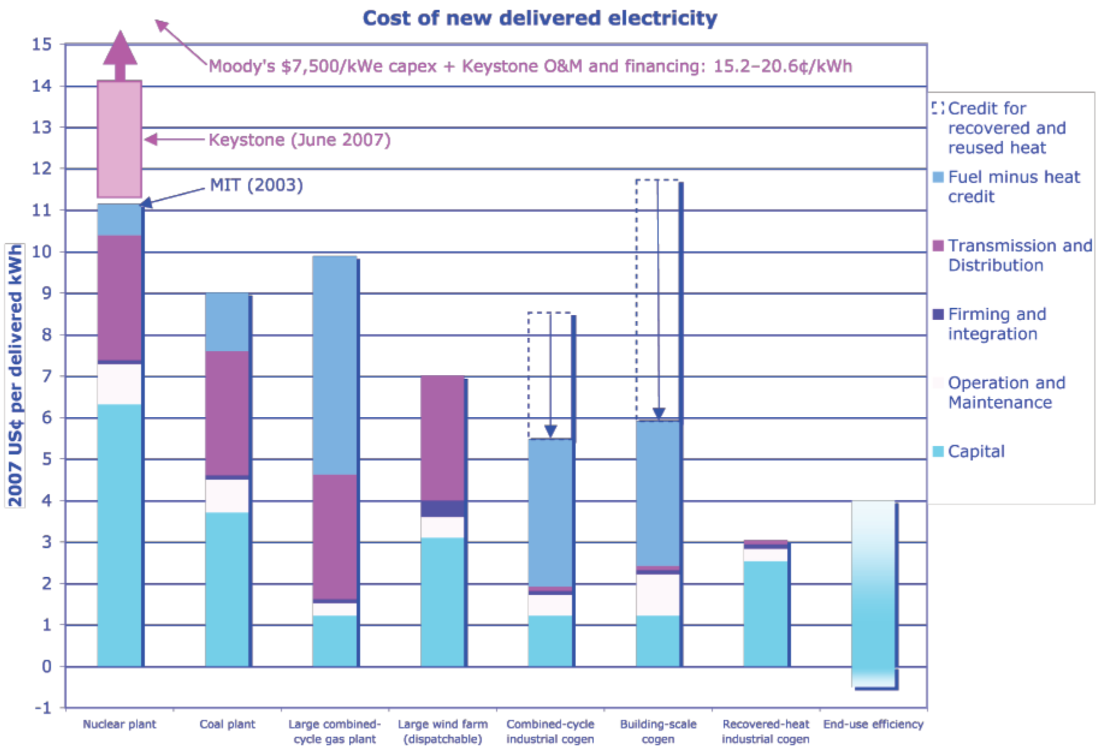


Figure 5.14 A comparison of the cost of making and delivering a new firm kWh of electrical services in the United States, based on empirical ~2007 market costs and prices.
Source: Lovins, Sheikh and Markevich (2009, p. 4)

5.5 Energy security and climate change

Aspects of energy security are closely linked to climate policy. Energy security problems stem from three broad sources: (1) extreme events, (2) inadequate market structures, and (3) resource concentration. These categories of supply-side energy insecurity can be broken down into seven root causes of energy insecurity: extreme weather; large scale accidents; acts of terrorism; labour strikes; inadequate investment in new capacity; load balancing failure in electricity markets; and supply shortfall linked to resource concentration (Table 5.6) (Ecofys, 2009).

Table 5.6 Energy security risks

Category	Type	Brief description
Extreme events	Extreme weather	Extreme weather events can temporarily disable energy infrastructures and the supply of energy. A recent example is the impact of Hurricane Katrina, which hit the Gulf of Mexico in 2005, disabling a significant portion of the US oil and gas production and processing capacity. There are however many other possible extreme weather events with potential energy security consequences including those which impact on the demand side (e.g. exceptionally cold or hot days) or on the supply side (e.g. reduced cooling water availability).
	Large scale accidents	Much like extreme weather events, accidents can lead to unplanned outages of key energy infrastructures.
	Acts of terrorism	Acts of terrorism against key infrastructures (e.g. refineries or pipelines) or bottlenecks along specific energy trade routes (e.g. the straight of Hormuz) can cause disruptions to energy systems.
	Strikes	Due to the strategic nature of energy, strikes or other forms of social unrest may specifically target the operation of key energy system components.
Inadequate market structure	Insufficient investments in new capacity	Market structures which fail to generate timely investments in key energy system infrastructures can contribute to making the system more vulnerable and ultimately generate energy insecurity.
	Load balancing failure in electricity markets	Because electricity is not storable in any meaningful volumes system operators must effectively balance supply and demand in real time to ensure system reliability. The task is challenging and requires that certain technical characteristics be met. When this is not the case systems sometime fail or do not operate in an efficient manner causing a loss of welfare for users.
Supply shortfall associated with resource concentration		Due to the concentration of resources in certain regions of the world, exploration and production as well as transport of fuels are also concentrated. This generates a certain degree of market power which can adversely affect energy systems.

Source: Ecofys (2009)

Climate change and climate change policy can both affect energy security. Extreme weather events and floods brought about by climate change can temporarily disable energy infrastructures. Climate change policy affects energy security in various ways. In general the EU climate policy package and CCS policy have led to an overall improvement in energy security in terms of a decrease in vulnerability (Ecofys, 2009, p. 23). A reduction in energy imports improves energy security, but energy security is more a problem for certain resources than others. All fossil fuels sourced from politically unstable regions outside the EU pose a security risk, but natural gas from Russia is viewed a particular risk given that the supply is politically charged. Energy security has become a matter for EU policy. In its Energy Security and Solidarity Action Plan the Commission has formulated five points of action:

1. Promoting infrastructure essential to the EU's energy needs, where the following number of cross-border infrastructures have been identified as energy security priorities of the Community: a Baltic interconnection, a Mediterranean Energy Ring, adequate North-South gas and electricity interconnections with Central and South-East Europe, a North Sea Offshore Grid, a Southern Gas Corridor and effective liquefied natural gas (LNG) suppliers to Europe.
2. A greater focus on energy in the EU's international relations
3. Improved oil and gas stocks and crisis response mechanisms
4. A new impetus on energy efficiency

5. Making better use of the EU's indigenous energy reserves

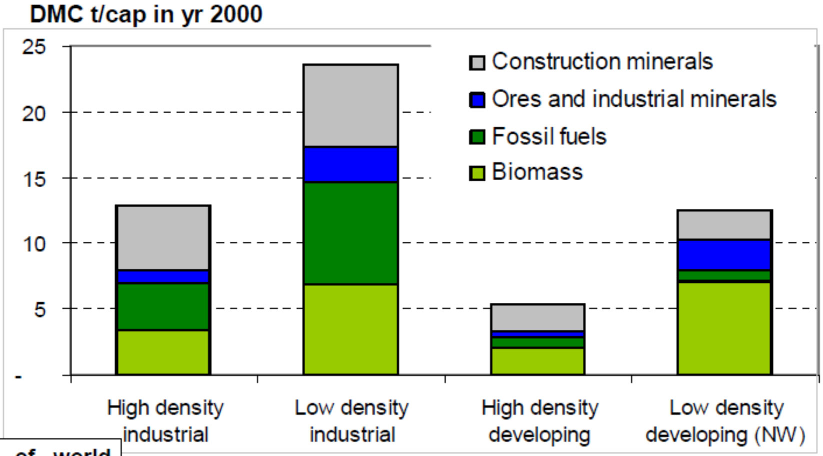
Energy efficiency and making better use of EU's indigenous energy reserve fits with climate protection. The other strategies may work against climate policy. The willingness to diversify energy supply for reasons of energy security works both for and against low-carbon technologies. Within the EU it is not to be expected that nations are unwilling to give up the exploitation of indigenous fossil fuels for reasons of energy security and jobs. The energy security risks of fossil fuels are well-known. But renewables also give rise to energy security problems. The intermittent nature of wind power and solar power makes them less secure than fossil fuels and nuclear power. Fluctuations in supply are less of a problem when using different renewables and load management may be used to match electricity demand with renewable supply. Biomass can deliver power on demand (and compensate for the intermittent nature of wind and solar power) as it is easily storable but is subject to seasonal fluctuations (DLR, 2006, p. 52). Renewables require excess capacity and power storage. Low-cost energy storage technologies are important for renewables; the greater the share of renewables (especially solar and wind) the greater the need for power storage. Renewable power from North Africa and the Middle East involves a political energy security risk. When imported from outside the EU, biomass may also involve a political energy security risk.

5.6 Implications for climate change policy

In this chapter we focus on three resource issues relevant to climate change: (1) depletion of fossil fuels especially conventional oil, (2) the dependence of low-carbon energy technologies on critical materials and (3) differences in renewable energy opportunities in Europe.

Resource scarcity does not appear to have caused a real constraint on economic development over the last 100 years. Overall material extraction rose a by a factor of eight in absolute terms and by a factor of two on a per capita basis. This increase in mineral resources use was not linked to price increases for minerals. Depletion of non-renewable natural resources does not automatically lead to increases in prices. It is possible that prices will rise quite in the coming decades, but this is not certain. Oil prices are expected to be higher because of peak oil and growing world demand. In its last world Energy Outlook the IEA expects the price of oil to be above 100 USD per barrel after 2015 and to reach a level of 200 USD in 2035 (IEA, 2010).

Fossil fuel use is higher in industrial countries than in developing countries as expected, but there is a relationship between fossil fuel use and density of population: fossil fuel use is lower in high density industrial area than in low-density industrial areas (Figure 5.16). The shift to urbanisation which is projected for the coming decades may thus help to reduce fossil fuel use in relative terms.



	High density industrial	Low density industrial	High density developing	Low density developing (NW)
Share of world population	**13%**	**6%**	**62%**	**6%**
Pop density	**123**	**12**	**140**	**19**

Figure 5.15 Average metabolic rates (resource use in tons / capita) by development status and population density
Source: Krausmann et al. 2008 in Fischer-Kowalski and Swilling (2011, p.28)

The depletion of conventional oil however is not good news for GHG reduction when conventional oil is substituted by non-conventional oil whose production is more energy-intensive. It is good news relatively speaking if conventional oil is substituted by low carbon substitutes. The oil industry is largely focusing its investment on natural gas, especially remote gas which is liquified and can be used in internal combustion engines in transport (motor cars, trucks and airplanes). This does not lead to much lower carbon emissions unless the carbon is being sequestered. Gas can be used for electricity production, and it makes sense to use natural gas in the transition period to CCS to meet growing demand for electricity if one is to use fossil fuels (the carbon content of natural gas is 14.4 metric per terajoule, compared to 25.4 for coal and 19.9 for oil).[70]

The era of cheap oil is over, but **one should not expect oil prices to increase every year as a result of higher costs for oil production.** This means that we cannot rely on higher market prices to improve the competitiveness of renewables. Growing demand from large rapidly growing countries such as China and India will drive up prices but will also give rise to increases in supply which has a downward effect on prices. Relatively modest price increases are foreseen for fossil fuels. This will reduce the costs gap for renewables but won't make them fully competitive for power generation.

Fossil fuel substitution may make things worse from a climate protection point of view and there is a clear climate policy issue of promoting a substitution of *low*-carbon fossil fuels for high-carbon fossil fuels but it should be remembered that existing coal power plants cannot be converted to natural gas[71] and that prices and security of supply reasons make coal the favoured fossil fuel in many parts of the world, including Europe where carbon emissions from power plants fall under an emission trading scheme.

Energy security can conflict with climate change. Fears about the reliability of Russia may work against import of natural gas, a relatively clean fossil fuel. Importing solar power from North Africa, as proposed in the Desertec project,[72] also suffers from energy security risks. From an energy security point of view it is more desirable to invest in concentrated solar power in south European countries. A supergrid involving the use of multiple renewables

[70] https://www.eurovent-marketintelligence.eu/carbon-content-of-fossil-fuels_fr_05_04_02.html

[71] Technically it is possible to retrofit them but it is more economical to construct new gas-fired units than to retrofit existing coal-fired units to burn natural gas. http://www.sourcewatch.org/index.php?title=Coal_plant_conversion_projects

[72] DESERTEC is a plan for making use of solar energy and wind energy in deserts near Europe (in North Africa and the Middle East). The plan is proposed by an industrial consortium of European companies and the DESERTEC Foundation. http://en.wikipedia.org/wiki/Desertec

(solar, wind and biomass) in various nations (including those in North Africa where there is plentiful sun and large potential to produce solar power) helps to balance the EU power system and is both desirable from an energy security and climate change point of view.

Renewables cannot take the place of fossil fuels in the short term because of costs and planning contraints[73] (nor can nuclear because nuclear power plants take three to six years to build; with planning permission also requiring a few years, it may take 10 years for a new nuclear plant to come into operation in Europe). Given that CCS is also not a short term option, **policy should focus on energy efficiency.** Given that the energy efficiency of existing appliances cannot be changed (except in exceptional cases) a clear target for policy is the energy efficiency of buildings (existing stock and buildings yet to be constructed). Prolongation of nuclear plants is another option, attractive to utilities because there are no depreciation costs and dismantling costs will be postponed. The recent nuclear problems in Fukushima in Japan however can be expected to give rise to extra concerns about the saftely of old plants, which may work against prolongation of existing plants. The loss of trust in safety of nuclear plants could work against the building of new plants and probably will lead to cost-increasing safety requirements.

In the absence of CCS for achieving CO_2 reductions we need to simply use less fossil fuels and this requires carbon constraining policies. **Clearly what should *not* be done is to subsidise the use of fossil fuels or to give away carbon emission rights for free to energy intensive sectors**. In allocating emission rights national governments as well as the European Commission are under a lot pressure from energy-intensive industries to provide those rights for free. The Commission gave in to those pressures out of fears of job losses and carbon leakage. One of the sectors receiving free carbon rights under the European Emission Trading System for carbon is the cement industry. Low-cost carbon reductions from material substitution are being missed because of free distribution of carbon rights. This would not be a major problem if the cement industry was not a major contributor of carbon emissions, which it is. Cement production is responsible for 5 per cent of man-made global emissions, half from the cement-manufacturing process and half from direct energy use, according to the IPCC. The cement industry "accounts for more CO_2 than all of the world's aviation, by a large margin, and in Europe for about 10 per cent of all the emissions covered by the EU ETS", says a report by Carbon Trust, a UK government organisation tasked with achieving carbon reductions (Carbon Trust, 2010, p. 46). Giving away carbon allowances for free allows the companies to sell these at a profit or to charge consumers for incremental carbon costs despite the free allocation of carbon rights. There is evidence that this is happening[74], which is undermining innovation in low-carbon cement.[75] The problem has been recognised and partly addressed. From 2013 the allowances will – although for free – be allocated based on sectoral benchmarks resulting from the Top 10 performers. The overall cap, i.e. the quantity of allowances available, will be steadily reduced until 2020. Aviation will be brought under the ETS but emissions from vehicles not. Greenhouse gas emissions from *new* vehicles are controlled through CO_2 regulations which are being sharpened. Transport is a sector for which GHG emissions are expected to rise in the EU until around 2030.[76]

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[73] The European wind power association (EWEA) projects 16.7% electricity from wind by 2020 (EWEA "Pure Power" (2009). The European photovoltaic industry association (EPIA) predicts 12% of electricity demand from PV by 2020 for Europe (under paradigm shift scenario) "Solar Generation 6", pp. 6, EPIA Feb. 2011.

[74] The carbon trust estimates that between 10-40 per cent of the carbon "cost" has been passed through in the EU ETS phase 1 (Carbon Trust, 2010, p. 47). Theoretical models estimate that between 33-90 per cent of the costs will be passed on, depending on market structure and location (Carbon Trust, 2010, p. 47).

[75] CO_2 emissions from Alkali-activated cement, an innovation of the Dutch company ASCEM, are estimated to be 52% lower than those for Portland cement (ASCEM, 2008). In Australia, the company TecEco is working on an "eco-cement" in which a large part (between 50-90 %) of the Portland cement is replaced with reactive magnesia. CO_2 emissions from the manufacture of eco-cement are said to be almost 20 per cent lower than from Portland cement production. Both innovations are promising but large cement companies are criticised for not taking action, to be "just standing on the side lines watching" according to TecEco Managing Director John Harrison.

http://www.tececo.com/files/publicity/RichensJamesEndsReportCementFirmsSnubLowCarbonEcoCementJuly2003.pdf

[76] In the past 20 years, GHG emissions fell in all sectors expect for transport where GHG emissions increased with 30%. In 2030, GHG emissions from European transport (excl. maritime) are estimated between +20 and -9% (European Commission, 2011a, p. 6)

The **policy implications of the critical materials issue for emerging low-carbon energy technologies are less clear**. Here we can expect market forces to generate substitutes but it is unclear whether this will happen in time and whether market-based processes will not produce a too narrow range of alternatives. Whereas the case of government intervention is firmly established for pollution related-problems, the academic literature disagrees on whether resource scarcity or competition for scarce resources presents a fundamental problem or is easily solved by the market (UNEP, 2010, p. 8).

Public support of research into alternatives may be warranted to widen the search for substitute materials and speed up the time by which they are available. Another solution is to stimulate recycling of critical materials. Both options are being proposed by the Ad-hoc Working Group[77] on defining critical raw materials group, which came up with the following implications.

For research and innovation policy, the Group "recommends that substitution should be encouraged, notably by promoting research on substitutes for critical raw materials in different applications and to increase opportunities under EU RTD Framework Programmes" (EC, 2010a, p. 9).

For waste policy, the Group "recommends that policy actions are undertaken to **make recycling of raw materials or raw material-containing products more efficient**, in particular by:

- mobilising End of Life products with critical raw materials for proper collection instead of stockpiling them in households (hibernating) or discarding them into landfill or incineration;
- improving overall organisation, logistics and efficiency of recycling chains, focusing on interfaces and a system approach;
- preventing illegal exports of End of Life products containing critical raw materials and increasing transparency in flow;
- promoting research on system optimisation and recycling of technically-challenging products and substances." (p. 9)

There are innovation policy elements in several of these.

For resource productivity policy (a very much underdeveloped policy field), the Group "recommends that the overall material efficiency of critical raw materials should be achieved by minimising the raw material used to obtain a specific product function and by minimising raw material losses into residues from where they cannot be economically recovered. The measures should be evaluated with regard to impacts on environmental and economic performance over the entire value chain."(pp. 9-10)

Nanomaterials offer opportunities to create special materials whose use may help to save fossil fuel-based energy and reduce carbon emissions. Examples of application are carbon nanofiber car and organic solar cells in which nano-particles increase the energy efficiency of solar cells. Further research is needed, whether or not more funding for nanomaterials is needed. There are also risk issues which need to be addressed and issues of recycling. A recent Friends of the Earth report, casts a very critical eye on nanotechnology, pointing to high energy use during production, health risks, and low delivery on high promises:

"Green nano does not currently exist in any meaningful sense – as an area of research, as industry practice, or as a viable alternative to the status quo. Yes, the environmental burden of nanomaterials manufacture could certainly be reduced, but neither researchers nor industry will know enough in the near future to design environmentally benign nanomaterials or methods for their manufacture. In the meantime, the inconvenient truth is that nanomaterials manufacturing is a dirty, energy and water intensive process that both uses and produces many toxic chemicals, while nanomaterials themselves pose serious and poorly understood health and environmental risks" (Friend of the Earth, 2010, p. 60).

[77] The Ad Hoc working group is created under the umbrella of the Raw Materials Supply Group, a stakeholder-based expert group chaired by DG Enterprise and Industry, comprising representatives from Member States, Industry and other stakeholder (EC, 2010a)

As general purpose technology, nanotechnology has many applications, some of which help to secure climate mitigation benefits, some of which do just the opposite. An example of very climate unfriendly application is the use of nanotechnology to enhance oil recovery.

In Europe resource efficiency is coming up as an issue. Resource efficiency is one of the flagship initiatives of the Europe 2020 strategy. In the Communication on resource efficiency (COM(2011) 21 final), the European Commission outlines a series of initiatives, of which the low-carbon economy 2050 roadmap is one (COM(2011, 112 final). Other initiatives are the European Energy Efficiency Plan 2020 and the White Paper on the future of Transport. As the analysis of this chapter has shown, resource scarcity in itself does not call for resource efficiency but resource efficiency will produce a suite of benefits in the form of energy savings and reduced GHG emissions. Other benefits are: reduced imports of fossil fuels and health benefits from reduced levels of air pollution (soot, SO_x, NO_X, hydrocarbons, ..). The production of material goods is responsible for 50% of energy use in Germany, which shows the importance of material efficiency strategies aiming a remanufacturing or reuse and extending product lifetime (Nathani, 2006). With regard to the potential of recycling, materials that are potentially recyclable account for an energy demand of 3600 PJ, whereas (currently) non-recycable products are responsible for an energy consumption of 2000 PJ in Germany (figures for year 2000) – suggesting a large potential for energy saving through recycling (Nathani, 2006, p. 15).

This suggests that a resource decoupling approach which seeks to reduce the amount of resource use and increase recycling makes sense from a climate protection point of view. Bleischwitz (2009) argues for a materials policy, aimed at reducing material intensity. According to Bleischwitz (2010, p.240), "the challenge is to overcome the business model of a primary production company delivering basic materials and develop competences towards a fully integrated material flow company network, with high knowledge intensity, customer orientation, worldwide logistics, high-level recycling and a long time horizon. Such base metal companies will manage products, flows and stocks". There appears to be a role for innovation policy to facilitate those competences and the creation of business models. Material recycling requires joined-up efforts from government actors and private companies. Government actors have an important role to play in the creation of framework conditions and the creation of an infrastructure of collection, separation and quality control. The efficiency of such infrastructures is something for innovation policy. Two relevant initiatives are:

- the European Commission's lead market approach for the recycling industry
- European multi-stakeholder process launched by the Dutch Ministry of the Environment (VROM), the European Partners for the Environment (EPE) and the Wuppertal Institute in partnership with OVAM, ACR+ and ESKTN on "Chain approach in raw materials and waste".

They are examples of green growth initiatives, in which economic growth is made to work for climate change rather than against it. Climate policy may be able to piggy back on other issues, such as energy security, clean air policy, resource decoupling, transport policy (the promotion of cycling, congestion charging), advanced materials policy, industrial policy etc., but, as this chapter has shown, non-climate policies may also erect barriers for it through the protection of national energy-intensive industries, coal industries and the car industry as well as the facilitation of car-mobility.

There are many good reasons for a materials policy and for making dematerialisation an official target for policy. This is being recognised in the recent communication from the European Commission "A resource-efficient Europe" which states that: "Using resource more efficiently will help us achieve many of the EU's objectives. It will be key in making progress to deal with climate change to achieve our targets of reducing EU greenhouse gas emissions by 80 to 95% by 2050. It is needed to protect valuable ecological assets, the services they provide and the quality of life for present and future generations. (…) By reducing reliance on increasingly scarce fuels and materials, boosting resource efficiency can also improve the security of Europe's supply of raw materials and make the EU's economy more resilient to future increases in global energy and commodity prices". [78]The EU Raw materials Strategy as well as the recent OECD report on green growth indicators call for an absolute decoupling between GDP and primary materials. The setting of specific targets for resource productivity by the EU and Member States will be the next important step.

[78] COM(2011) 21 final, p. 2. According to COM(2011) 112 final A Roadmap for moving to a competitive low carbon economy in 2050, implementation of policies to achieve a 80% reduction in GHG emissions by 2050 will reduce the EU's average fuel costs by between €175 billion and €320 billion per year, thanks to energy efficiency and the switch to domestically produced low carbon energy sources. The increase in public and private investment is estimated at 270 billion annually, which is 1.5% of EU GDP per annum.

European Commission
Enterprise and Industry

6 INNOVATION FOR DEALING WITH CLIMATE CHANGE

6.1 Introduction

This chapter proposes a four-level typology of innovation that is of relevance to climate change. The typology creates a framework for policy interventions, which are discussed in the next chapter. The typology ranges from incremental innovations, which provide few policy challenges, to transformative innovations that are difficult to manage and which require long-term planning.

The structure of the chapter is as follows. Section 6.2 describes our typology of innovation. Section 6.3 focuses on transformative innovations and examines the need to target consumer choices and behaviour. It also looks at reduced growth and green growth as a strategy for mitigating greenhouse gases. Section 6.4 examines the innovation requirements for adaptation and geo-engineering and section 6.5 draws the conclusions.

6.2 Typology of innovation

A diverse range of innovations are required to reduce greenhouse gas emissions to sustainable levels and to adapt to expected climate changes that are largely inevitable, due to the failure of nations to reduce past emissions. The types of policies that are relevant to promoting these innovations will depend on the technological, economic and social characteristics of the innovation. An important aspect of innovations is whether or not they are compatible with existing socio-technological regimes or if their full deployment requires a change in the current regime. A regime can be defined as an existing set of social and economic factors that have co-evolved with a specific technology, such that these three factors mutually reinforce each other. Examples of regimes are given below.

Many different typologies of innovation have been developed that are relevant to the challenge of climate change. Based on the relevant literature, we propose the following four-level typology:

- ***Incremental innovations*** involve upgrades to existing technologies and business practices, producing innovations that fit easily within existing technological regimes. An example is the gradual increase in the efficiency of wind turbines through technological improvements that increased the length of windmill vanes.

- ***Techno-fixes*** require the development and application of a new knowledge base to correct problems within a regime, but leave the regime intact. An example is carbon capture and storage (CCS) or replacing petrol with biofuels for transport uses. Both require new knowledge bases. For example, the production of biofuels requires biotechnological knowledge to be able to produce high energy density biofuels from living organisms at low cost. But, it does not require a change in automobile engines or a new infrastructure to distribute biofuels, which can be provided to motorists through existing filling stations. Techno-fixes changes some practices at the supply side, but generally have minimal impacts on the demand side.

- ***Social innovations*** involve a significant change in user practices and social institutions but minor changes (if any) in technology, other than new organisational forms or business models. An example is organised car sharing where people do not own a car and consequently do not use a car for most of their trips.

- ***Transformative innovations*** are system-wide novelties (Steward, 2008) that involve fundamental changes in the way things are done. They frequently require both new knowledge bases and new infrastructures and can have far-reaching social and economic effects, resulting in a shift to an entirely new regime.[79] An

[79] In the innovation literature these fundamental changes in sectors or entire economies are variously referred to as “new technological systems” (Freeman and Perez, 1988), “technological regime shifts” (Kemp, 1994; Rip and Kemp 1998), “socio-technical regime shifts” (Geels, 2002; 2004), system innovation (Elzen et al., 2004; Geels, 2005; Tukker et al. 2008) and “transition” (Geels, 2005, Grin et al., 2010).

example is a transition from fossil fuel transportation systems to electrical transportation systems. This would require new infrastructure for an expanded electrical grid, electrical storage systems, and electrical recharging stations.

An alternative typology that is relevant here is to classify innovation by their economic effects: incremental, disruptive or radical.[80] This typology is similar to the four-level typology given above, except that it does not explicitly include the interactions between society and technology and it does not encompass largely social innovations.

Following Smith (2009), incremental innovations are based on discoveries within a well-understood technological paradigm or product system and are largely identical to incremental innovations in the four-level typology given above. As a general principle, incremental innovations and the products that incorporate them should not need public support for R&D, although they may need short or medium term subsidies to encourage companies to invest in them. An example is subsidies for electricity produced by wind turbines.

A disruptive technology involves new knowledge bases that replace an existing way of doing things. They are similar to techno-fixes. Replacing petrol with biofuels would disrupt business models based on petroleum products, but would have minimal effects on social practices. Due to long development times, disruptive technologies to address climate change are unlikely to develop quickly enough without government support for R&D and for pilot projects. Disruptive innovations as competence destroying innovations may occur through the normal operation of markets. [81]

A radical technology is similar to a transformative innovation in that it requires both new knowledge bases and new infrastructure. Radical or transformative technologies require government support for new infrastructure and structural embedment.

The specific type of innovation – incremental, techno-fix, social, or transformative – is of relevance to innovation policy because of the differences in their potential economic impacts. Figure 6.1 charts the economic and social effects of each of these four types of innovation by the degree to which a technology requires new knowledge bases.

Regime changing innovations are of particular importance because they create far more complex problems for policy and for society than either incremental innovations or techno-fixes. It is therefore worthwhile to explore the differences between regime changing innovations and other types of innovations.

Hydrogen fuel cell vehicles are techno-fixes because they require new knowledge bases, but they are not a transformative innovation in terms of user practices and do not require a significant regime change. Hydrogen fuel cell cars comply with current preferences and user practices of range and speed. A regime change would occur if the majority of people started to use bicycles and public transport instead of a car, for instance through social innovations that lead to changes in company strategies and transport planning. Public transport companies would need to provide attractive alternatives to car drivers in addition to traditional public transport users and transport planning would need to give precedence to non-motorised forms of transport. Although this would require a regime change, the innovation would not be transformative because it would not require new technology or infrastructure.

[80] There is little agreement among innovation scholars in the use of the terms incremental, radical, and discontinuous innovations (Garcia and Calantone, 2002). Rothwell and Gardiner (1988) would label the electrical typewriter as an incremental innovation, Kleinschmidt and Cooper (1991) as a moderate innovation and Abernathy and Clark (1985) would call it a revolutionary innovation (Garcia and Calantone, 2002).

[81] Christensen (1997) makes a distinction between low-end and new-market disruptive innovations. A new-market disruptive innovation is often aimed at special consumers, while a low-end disruptive innovation is focused on mainstream customers who are interested in a low-cost and lower-performance alternative.

User, market & institutional practices		
Disrupt existing practices	**Social innovation** - Organised car-sharing - Integrated transit - Planning changes	**Transformative innovation** - Electrical transport system - Renewable-electric power supply
Sustain existing practices	**Incremental innovation** - improved windmills - Hybrid vehicles - Low energy appliances - Passive housing - Concentrating solar power	**Techno-fixes** - Carbon capture & storage - Hydrogen cars - Biofuels - Geothermal power
	Minor	Major

Change in technological knowledge & competences

Figure 6.1 Typology of innovation
Source: Authors based on Abernathy and Clark (1985) and Dijk (2010)

Car sharing is another example of a social innovation that could be economically disruptive to automobile manufacturers and associated companies *if* it substantially reduces the institution of private car ownership. It is still about using a car, but cars would be used more selectively, often in combination with other modes of transport.

Transformative innovations are disruptive from the point of view of existing business and societies (Steward, 2008; Courvisanos, 2009). A transformative innovation such as electrical vehicles combined with a smart grid, with batteries being used for power storage, would have disruptive effects throughout an economy, create new business models (manufacture and re-charging of electrical vehicles), and lead to the gradual demise of other business models (petroleum refining, transport, and distribution). Some configurations are more radical and disruptive than others and the challenge for business actors and innovation policy is to find new business models or "configurations that work" (Rip and Kemp, 1998). From a climate change policy perspective, new configurations need to maximise greenhouse gas reductions, something which cannot be achieved through innovation policy alone.

Transformative innovation can only be envisioned imperfectly at the beginning, given the technical, economic and other uncertainties. The inventor and the potential user will usually not be able to judge fully the potential benefits and costs of transformative change. Wieczorek and Berkhout (2009) note that increasingly 'radical' innovations will create a growing number of problems to solve, "over the benefits and costs of the alternatives, over the distribution of costs and benefits, over new economic and technical uncertainties about the consequences of the alternative". It usually takes a few decades for transformative innovation to move from the margins to the mainstream (Steward, 2008). Smith (2009) summarizes some of the factors that result in very long time horizons for transformative innovations (See Box 6.1). The time can be shortened through public investment in infrastructure and policies to reduce the risks associated with private investment.

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Box 6.1 Factors driving long time horizons for transformative innovations

- Processes of "collective invention" through which inventors, engineers, entrepreneurs and government agencies dispersed widely in time and space work on technical problems and design configurations.
- Patronage of emerging technologies and their knowledge bases either by individuals, societies or governments, which protects the new technology during the (often long) development phase.
- Niche markets through which emerging technologies are protected from the full brunt of competition while they are developed.
- Direct or indirect government support for a technology and/or the infrastructure for it.
- Multiple search processes, creating difficulties of choice and considerable risks.
- Major changes in governance, social organisation, production methods and management, which themselves may involve long time periods and have their own dynamics.

Source: Smith, 2009. Smith uses the term 'radical innovations' but his concept is very similar to a transformative innovation.

The challenge for innovation policy when faced with transformative innovation is not just to help innovations go down the learning curve through performance-enhancing research, but to facilitate socio-technical alignment, which help to build a new system, based on both new technology and new communities of practice.[82]

In the case of new technologies, there is often a long competitive race between an emerging and mature technology. This applies to both techno-fixes and to technologies that are part of a transformative innovation. For a renewable energy source such as concentrated solar power (CSP), learning by using and experience with scaling up can be expected to reduce the costs per kWh, but in a pure market system the cost of producing electricity through burning fossil fuels will also decline in response to competition from CSP. Subsidies or carbon taxes will be needed to tilt the costs in favour of CSP and to ensure sufficient improvements so that the cost of CSP approaches that of fossil fuels. Ideally, at some point, companies would shift new investment from coal to CSP without financial subsidies.

The particular type of innovation is not static but can co-evolve with changes in markets and society. An innovation initially used to preserve a system may become part of a new regime. Road pricing is a good example. As an organisational and a technological innovation it alleviates the most important problem for car drivers: longer travel times caused by congestion. Road pricing consequently is regime *preserving* for automobile use. However, road pricing can also encourage people to shift to other modes of transport and therefore contribute to a regime shift. This example shows that regimes are not entirely defined on the basis of technologies, as technologies can be used either to preserve regimes or to encourage a shift to a different regime. In many cases, new technologies are used to preserve regimes. The examples also highlight the importance of social innovation.

A regime-preserving innovation may become a regime-altering innovation through a fit-stretch pattern in a changing landscape (Figure 6.2).

[82] Communities of practice are groups of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly (Lave and Wenger, 1998).

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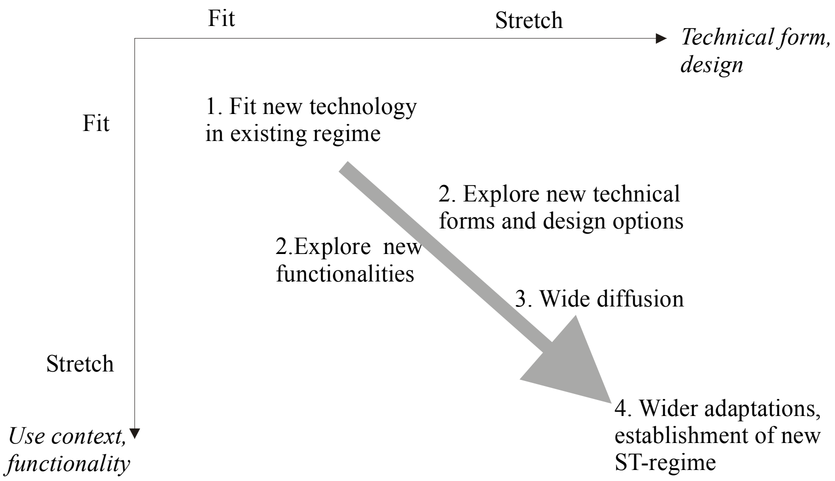

Figure 6.2 Fit–stretch pattern in the co-evolution of form and function
Source: Geels (2005b)

The innovations may 'move around'. An example is when organised car sharing (OCS) becomes an element of intermodal travel, where people regularly combine different modes of transport (this requires integrated bus and train schedules, the availability and use of smart-phone based real-time information, and inter-modal transfer points). When battery electric vehicles are being used within organised car-sharing schemes, such vehicles are being used in a more transformative way (under the assumption that OCS users decide to get rid of their old car). General purpose technologies can be used in a transformative and non-transformative way. The smart grid - a vision of jointly managing power supply and demand using information technology[83] – can be controlled by existing utilities or by smart integrators who do not own or sell the power that is delivered by the grid (Fox-Penner, 2010). In the latter case, technical innovation could lead to new business models.

For technologically disruptive and radical innovations, there is often a pattern of niche accumulation as the technology is applicable to a growing number of applications. Increasingly, this pattern could also apply to social innovation. The first market niche often depends on special support and circumstances, such as military subsidies (as was the case with computers) or green consumers that are willing to pay a premium price. If the cost and functions of the technology improve over this gestation period, it may become commercially viable in other market niches. Broader diffusion tends to follow a pattern of niche-accumulation, with the technology entering increasingly larger market niches.

These market niches further facilitate learning processes, the build-up of a constituency, and improvements in the cost/performance ratio. While these processes contribute to internal momentum, the breakthrough into mainstream markets is often slow. In respect to climate change, the momentum may be unacceptably slow, requiring policy assistance.

The drivers, time span and policy role are very different for incremental innovations, social innovations, regime-preserving techno-fixes, and regime shifting transformative innovations. Whereas incremental innovation occurs through the normal operation of markets, techno-fixes and transformative innovations with environmental benefits are less likely to emerge under these conditions. Regulation and wider institutional changes are required to encourage a transition to a low carbon economy (Kemp et al, 2007; Voss et al., 2009).

[83] A smart grid is an umbrella term for which there is no agreed definition. An example definition is: „a smart grid delivers electricity from suppliers to consumers using two-way digital technology to control appliances at consumers' homes to save energy, reduce cost and increase reliability and transparency" (from en.wikipedia.org/wiki/Smart_grid). The stated positive effects are hoped for effects. Smart grid can produce carbon reductions directly through reduced energy and indirectly by facilitating a shift to low-carbon energy technologies.

The prevention of dangerous climate change will require reductions of GHG emissions by more than 80% by 2050, which will require transformative changes in energy production and use. According to the ECF study "*achieving the 80% reduction means nothing less than a transition to a new energy system both in the way energy is used and in the way it is produced. It requires a transformation across all energy related emitting sectors, moving capital into new sectors such as low-carbon energy generation, smart grids, electric vehicles and heat pumps*" (ECF, 2010, volume 1, p. 9). Even a 50% reduction is viewed to require "major improvements in energy efficiency, the near-decarbonisation of the electricity sector and the introduction of new low-carbon technologies in the industry, buildings and transport sectors" (IEA, 2010, p. 46). Such a change is said to amount to an energy technology "revolution", requiring "unprecedented intervention by governments in developing policies that work with and influence energy and consumer markets to achieve this outcome" (IEA, 2010, p. 460).

The decarbonisation of the energy sector is commonly viewed as constituting a transition. However, if we apply the innovation typology developed above, we can see that the transformation can be disaggregated into a range of different types of innovations, which require different policy approaches.

6.3 Transitions

The fundamental problem facing innovation policy to prevent dangerous global warming is how to encourage a transition from a fossil-fuel economy to a zero carbon economy in a way that limits costs, discomfort and the creation of new problems. In this section we examine the theory of socio-technological transitions, as developed by evolutionary economists working on innovation and scholars examining the interplay between science, technology and society.

A recurrent theme in the literature is that innovation, in particular transformative innovation, is part of wider processes of change and is shaped by framework conditions. Innovations themselves also shape the dynamics of supply and demand, which mean that there is two-way relationship between technology and society.[84] Technology is not a neutral artefact, but develops through a 'socio-technical practice' that involves agents and processes (Smith and Stirling, 2010). Managing a transition requires understanding the factors that perturb an existing regime and how to guide its replacement by alternative systems.

Smith and Stirling (2010) comment that "some socio-technical systems are embedded more robustly than others, in the sense that they enjoy greater institutional support, larger economic significance, more supportive infrastructures, better integration with other social practices, and broader political legitimacy". These factors can help some systems to survive - and even to expand - even when they impose a considerable cost upon society. A good example is car-based modes of mobility, which cause carbon-emissions, local air pollution, noise, congestion, traffic accidents and deaths, social exclusion, land fragmentation, and problems of oil dependence and energy security (Cohen, 2006). The standard policy approach is to address these problems in a partial and piecemeal manner. Examples include the requirement for seat belts to reduce injuries from collisions, unleaded petrol to prevent neural damage from lead poisoning, road pricing to deal with congestion (a measure which has proved politically difficult to implement), fuel injection systems to increase the efficiency of engines and emission control systems. A common feature of these examples is that the solution is found *within* the system of automobility and not in alternative systems of mobility.

Another finding from the literature is that the government can only act against certain features of those systems; it cannot act altogether against such systems by forcing its discontinuation (Geels et al., 2010). Fears about job losses, pressure from industry, and citizen fears of life-style changes make it hard for policy makers to act forcefully against embedded socio-technical systems. Consequently it is easier for governments to help build new systems than to take apart those that exist. The British government was initially reluctant to invest in the construction of a highway system for motor cars, because of the dominant role of railway engineers in setting transport policy, the

[84] See Rip and Kemp, 1998; Geels, 2002, 2004; Elzen et al., 2004; Kemp et al. 2007; Smith and Stirling, 2010; Grin et al., 2010.

cost to the public budget and the absence of a constituency speaking forcefully in favour of road investment. The motor interests remained in an economic and political backwater well into the 1950s (Dudley and Chatterjee, 2010). This changed in the 1950s, when a conservative government decided to build roads, leading the government into the creation of a car regime (Dudley and Chatterjee, 2010).

For a transition to occur, a new technology must gradually develop from small, localised effects to broader economic effects, for instance by displacing other technologies for achieving the same ends. Over time, innovations become an element of the landscape, where they exert a pervasive influence on regimes. (Rip and Kemp, 1998; Rotmans et al., 2001; Geels, 2002, 2004; Grin et al., 2010).

A visual representation of transitions is provided by Geels (2002) (see Figure 6.3), who examines the cumulative nature of change, leading to dominant practices, types of knowledge and organisations. Transitions are viewed as the outcome of pressures on product regimes (cultural criticisms, regulations) and the (emergent) development of alternative systems, elements of which originate in product niches. Some products can break out of these niches as a result of learning economies and support from various actors (including incumbent companies, governments and consumers). The landscape of prices, values, associations and regulations exercise selection pressures but the economic, political and social landscape is undergoing change as well. Over time, a new dominant design may emerge after a period of ferment which constitutes the basis for improvement. There is an element of technological determinism in this story, although the literature stresses the role of social players and culture (Geels, 2004; Wieczorek and Berkhout, 2009; Smith and Stirling, 2010).[85]

Transitions have occurred in the past and will occur in the future. The transition to a zero carbon economy faces substantially larger barriers than have been faced in the past by other emerging technological systems, such as information technology (nurtured for many years by the US military), both because of the pressing need for a rapid transition, as outlined in Chapter 2, and because the transition must confront a cheap, plentiful, and socially embedded energy system based on fossil fuels. The transition will also face negative feedback effects. Low and zero carbon renewable energy is generally more costly than fossil fuels, but as renewables provide a larger share of energy, the demand for fossil fuels will decline, leading to price falls for fossil fuels that make renewables increasingly uncompetitive.[86]

[85] Empirical illustrations of this can be found in Geels (2006, 2007).

[86] We are not predicting an actual price fall for fossil fuels but only saying that the growth of RES will have a price-reducing effect on fossil fuels.

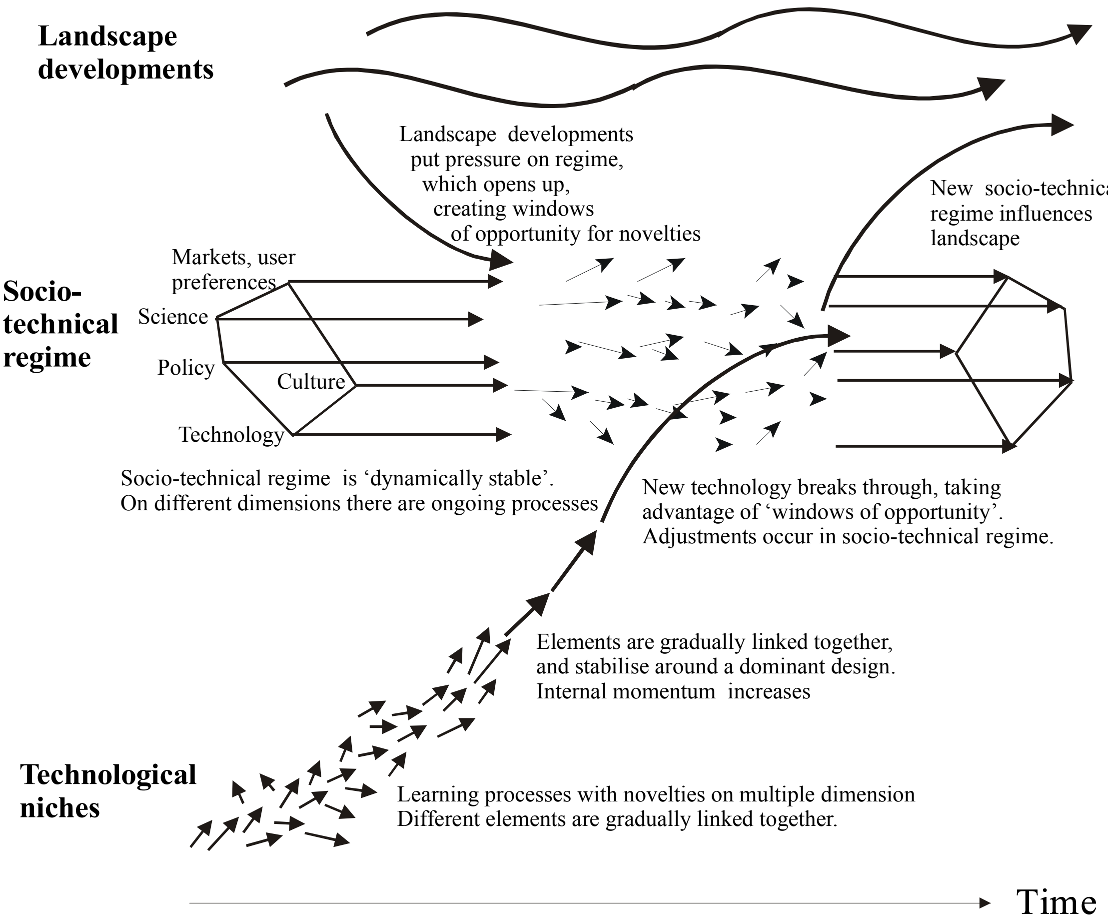

Figure 6.3 **A dynamic multi-level perspective on system innovations**
Source: Geels (2002, p. 1263)

6.3.1 Consumer choices and behaviour

Citizen support will be a key factor in the implementation of effective policies to prevent dangerous climate change because they are ultimately responsible for the large majority of GHG emissions (see Chapter 2, section 4). Policies to reduce GHG emissions through a carbon tax on major industrial producers can only go so far: achieving larger reductions will require confronting household energy use. Energy intensity of households increased in the 1990-2005 period, whereas it fell for other sectors (Figure 6.4).

Unfortunately, preventing dangerous climate change will require implementing some policies that if not actively opposed by a large share of citizens, are unlikely to be popular. An additional problem is that the benefits from a reduction in GHG emissions will largely be enjoyed by future generations.

Many citizens are resistant to paying more for environmentally beneficial technologies (Figure 6.5) or to make significant life style changes to reduce GHGs (Figure 6.6). Figure 6.5 shows that the majority of citizens in several countries are concerned about environmental and social aspects of products, but unwilling to act on these concerns for a number of reasons (won't compromise on convenience or quality). Consumers favour cost-efficient and convenient behavioural changes over alternatives that would save more carbon, but require a sacrifice.

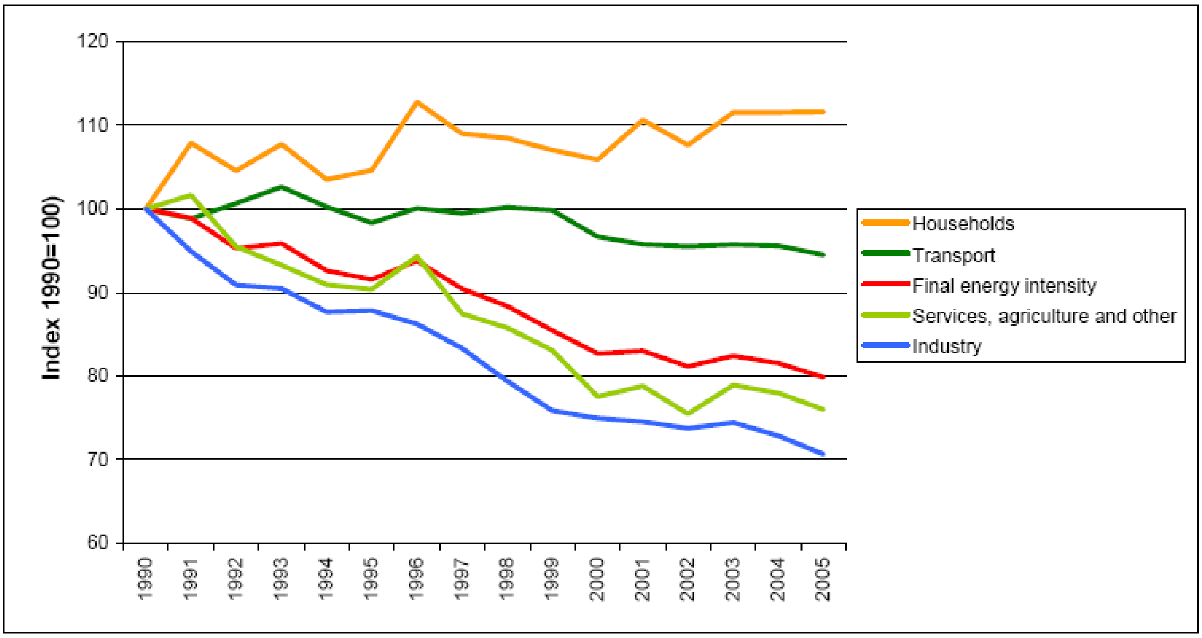

Figure 6.4 **Index of final energy intensity and energy intensity by sector, EU-27**

Source: EEA (EN21 Final Energy Consumption Intensity), based on Eurostat and the European Commission's Ameco database.

Note**:** Final energy intensities between sectors, and also the total final energy intensity, are not comparable, because the normalising variables are not the same. The indicator serves to highlight the evolution in energy intensity within each sector. The denominators for the total, household, transport, industry (excl. construction) and services (incl. agriculture) sector energy intensities are, respectively; GDP, population, GDP, Gross Value added in industry (excl. construction), and Gross Value Added in Services (incl. agriculture).

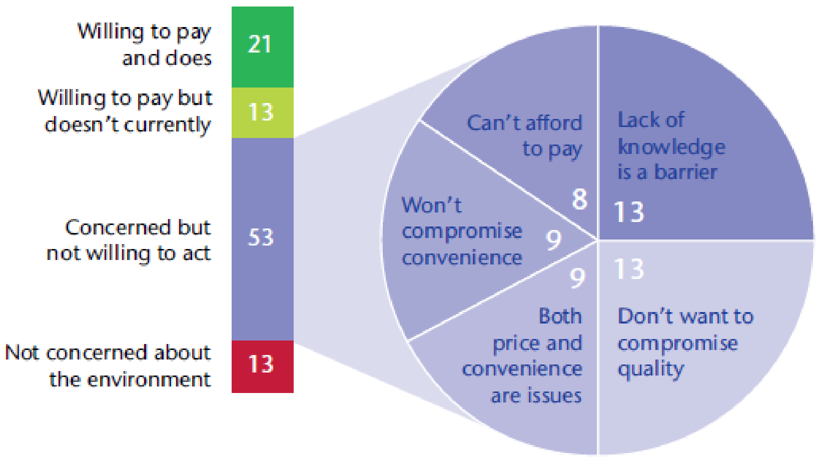

Figure 6.5 **Willingness of retail consumers in selected countries to pay for products with environmental & social benefits –** ***Survey of consumers in Brazil, Canada, China, France, Germany, India, the UK and the US***

Source: The McKinsey Quarterly, March 2008 (published in World Business Council for Sustainable Development, Sustainable consumption facts and trends, 2010. p. 17)

We should not expect consumers to willingly pay for green goods or suddenly to favour inconvenient lifestyles and changes in their diet. Green products have to provide functional or economic benefits before consumers will purchase them. An example of a functional benefit is the absence of motor noise in vehicles using electric propulsion (batteries and fuel cells). The lower cost of electricity compared to gasoline is an example of an economic benefit (which has to be gauged against the higher costs of batteries).

Changing diets, reducing the need for heating through changes in building design, and a shift to low-carbon modes of transport (walking, cycling and public transport) will help to reduce GHG emissions by households. Some options will be more important than others, and there is a need for assessing this on a life-cycle basis. The results can be surprising. One study for the US found that "shifting less than one week's worth of calories from red meat and dairy products to chicken, fish, eggs or a vegetable-based diet achieves more GHG reduction than buying all locally sourced food (Weber and Matthews, 2008, p. 3508, based on US figures).

Information about carbon footprints can help environmentally motivated consumers to reduce their carbon footprint, but cultural change plus government action is needed for the types of population-wide changes that are required to significantly reduce GHG emissions.

The role for public policy will differ from case to case. In general, there is a role for better information, supporting low-carbon innovation and phasing out high-carbon products. Changing the price of a product through a carbon tax or subsidy may not be enough. As Shove et al (1998) note, it is difficult to change consumer demand because of the products we own and houses we live in. A reduction in GHG emissions will require fundamental changes to the built environment:

> "End-users live in a world in which much of their consumption is already given. In the domestic setting, as in the office environment, consumers are confronted with a certain number of socket outlets, a boiler of a certain size, and a building fabric that is relatively difficult to alter. To understand more about the framing of energy decision making, we need to move along the supply chain and investigate the worlds of building contractors, subcontractors, and designers, as well as developers" (Shove et al., 1998, p. 313).

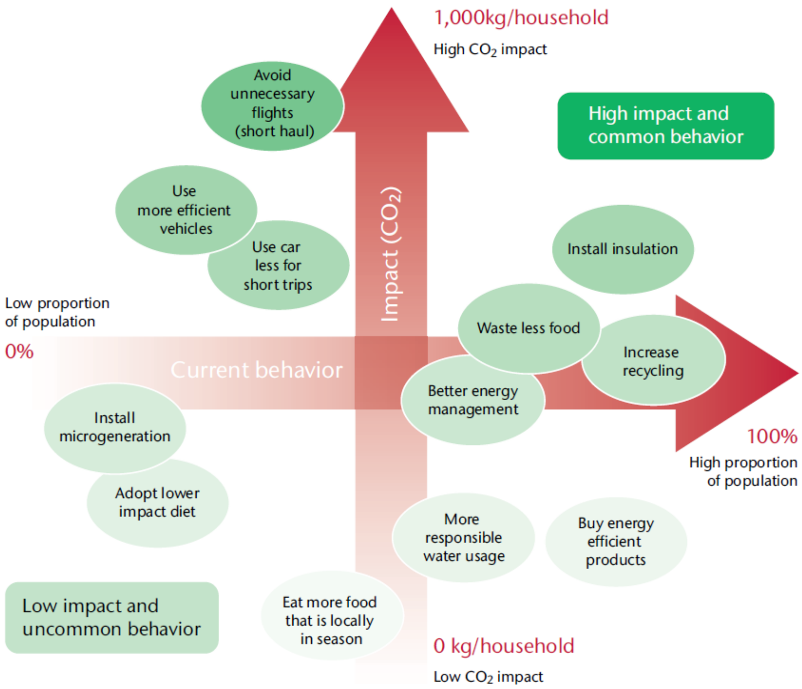

Figure 6.6 **Mapping of pro-environment options and behaviour**
Source: DEFRA (2007) *A Framework for Pro-Environmental Behaviours* (published WBCSD, 2008, p. 17)

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6.4 Climate adaptation and geo-engineering

Adaptation can help to protect investments, prevent agricultural losses and may reduce health risks and (future) insurance costs. Innovations to support adaptation differ from mitigation, in that they require specially designed solutions tailored to local circumstances. Cooperation with a group of actors has to be secured. Adaptation methods need to be incorporated into new and existing developments.

The climate adaptation implications for innovation have not been thought through yet, although most adaptation methods are likely to involve a mix of social and incremental innovations. The social innovations will often require changes to urban and rural planning (see Table 3.6). Climate adaptation technologies are supported through EU programmes for innovation, but it is difficult to get even a proximate idea of the level of support being granted to these technologies. There may be a need to do far more than is currently being done, both at the national level and at the EU level.[87]

There is also a need for helping developing countries deal with climate change, where the capability to adapt to climate changes is much smaller, while the consequences are more severe.

Geo-engineering

Although advocacy for geo-engineering is growing, no government has given it its full support due to safety concerns. Yet geo-engineering could be a useful short-term solution to excessive atmospheric CO_2 levels, if combined with concerted efforts to remove CO_2 from the air, for instance through biochar production, land use changes that create CO_2 sinks, or new technologies that can remove CO_2 from ambient air.

The Royal Society report calls for more research about geo-engineering methods, with such research being placed under a risk governance system, with the London Convention and Protocol system for regulation of ocean fertilisation as a possible model. The principal research and development requirements in the short term are for much improved modelling studies and small/medium scale experiments (e.g., laboratory experiments and field tests) (Royal Society, 2009, p. xii). Only those methods that are tested and found to be sufficiently safe should be considered for possible application on a larger scale.

Geo-engineering leads to difficult decisions about the optimal level of climate control, which will prove contentious among nations and are a potential source of conflict. There is a risk of unitary action by victims of climate change. In our scheme of things geo-engineering is a techno-fix option.

6.5 Conclusions

As we have seen in chapter 3, there are many things that policy can do to reduce GHGs by both industry and households. The price problem for low and zero carbon energy can be addressed by introducing a price on carbon that is high enough to provide a market for renewables. However, a price that is high enough to have an effect is politically difficult to implement at this time and would require a painful economic transition. Consequently, the design of transition policies is a key challenge.

The challenges of a transition away from a fossil fuel based energy system are referred to by many but few go deeply into these challenges. Smith (2009) argues that a much stronger coordinated effort must be made in order

[87] The 2010 World Development report Development and Climate Change notes that the "role of technology and innovation in adaptation has been much less studied than for mitigation, but it is clear that future climate conditions will be fundamentally different from the ones today. Responding to change outside of historical experience will require increased institutional coordination on a regional scale, new tools for planning and the ability to respond to multiple environmental pressures occurring concomitantly with climate change. Greater investments are needed to understanding vulnerability, in conducting iterative assessments, and in developing strategies for helping societies deal with a changing climate (Worldbank, 2010, p. 290-291).

to get out of the lock-in situation[88] that extends across not only economic sectors, but across current knowledge, education, engineering practices, infrastructure, public procurement and regulatory frameworks, all of which are parts of a technological regime - currently the hydrocarbon regime.

Options outside the hydrocarbon regime get support but governments have not yet accepted the task of phasing out fossil fuels. New coal-fired power plants get built, partly in the expectation that CCS will deal with the carbon emissions. But CCS is an unproven technology and still very expensive. A lot of money has been made available for demonstration projects (worldwide 26 billion USD according to the IEA, 2010a). In December 2009, the European Commission granted financial assistance to six CCS projects. The projects received an overall funding of €1 billion under the EEPR.[89] Social opposition and financial considerations have lead to the cancellation of CCS project. In Rotterdam, the Netherlands, a CCS project has been cancelled because of local opposition. In Finland a big CCS project was cancelled because of technological and financial risks.[90] CCS cannot be used for capturing emissions from diffuse points of emissions and it requires safe storage conditions which may not be locally available. There are significant limits to the use of CCS within Europe and governments are ill-advised to rely too strongly on this option. Perhaps it will deliver, but there is also a chance that it will not.

Making a transition to a low-carbon economy requires that all mitigation options are used. For the short term much can be achieved through energy efficiency and through changes in land-use (reversing deforestation, as discussed in Chapter 3). For the long-term, transformations in power generation, mobility, food systems and food consumption, as well as in waste management are needed. Consequently, the design of transition policies is a key challenge for actions to prevent dangerous climate change.

[88] Unruh (2000) has argued that we are „locked into carbon-intensive fossil-fuel based energy systems through a process of technological and institutional co-evolution, driving by path-dependent increasing returns to scale". The condition of carbon lock-in, as he calls it, arises through a combination of systematic forces that perpetuate fossil fuel-based infrastructures in spite of important negative externalities and the existence of cost-efficient alternatives (Unruh, 2000, p. 817).

[89] http://ec.europa.eu/energy/publications/doc/2010_eepr_brochure_co2_en.pdf

[90] http://www.electricityforum.com/news/nov10/Twocarboncaptureprojectsarescrapped.html

7 INNOVATION POLICY FOR CLIMATE CHANGE

7.1 Introduction

This chapter examines the implications for European innovation policy of climate change and associated problems due to demographic change in Europe and increasing resource scarcity from growing incomes, particularly in developing countries. We examine a number of themes for innovation policy such as policy learning, avoiding regulatory capture by special interests, focusing resources on areas where innovation is needed and stimulating an adequate range of options (diversity). We don't present policy as a single decision issue, but examine policy constraints and the need for policy to be forward-looking and adaptive.

The implications for innovation policy from changes that do not require a transformation in economic structures are considered in Section 2. This is the simplest policy challenge. A more difficult but fundamental challenge for policy is to promote transformative change, an issue taken up in Section 3. Section 4 examines twelve themes for long-term policies to support transformative change, drawing on innovation studies and the recent literature on transition management. Section 5 describes what is not well understood about transformative change. Section 6 provides the main policy conclusions.

7.2 Non transformative change

Energy technologies such as CCS and advanced biofuels support the current economic structure based on internal combustion engines for transport and the use of fossil fuels for generating electrical energy. No transformative changes in infrastructure would be required. These technologies are promising, but require large-scale demonstration projects to establish both technical and economic viability, together with the development of regulatory frameworks, strategic planning to implement an appropriate infrastructure, particularly for CCS, and public outreach and engagement. In some cases, the development of these technologies will require technology-specific support. This could take the form of tax credits for investment, incentives for customers, or regulations that mandate energy suppliers to purchase the output of a specific type of technology at higher-than market rates, for example through feed-in tariffs or renewable energy portfolio standards.

Solar power (whether photovoltaic or solar thermal) and wind power (an indirect form of solar energy) are technologies that break with the combustion paradigm. They have non-transformative characteristics in the sense that existing electrical grids can be extended to include them. Except for on-shore wind power, they are not currently competitive with the cost of fossil-fuel electricity generation. Their future development requires policies to establish a financial return that makes them competitive with other energy sources and attractive for private investment. Government policies and programmes should target support on initial costs, recognising that many of these renewable energy technologies are more capital-intensive than their conventional fuel counterparts, but with lower variable costs in operation (IEA, p. 468).

Innovation policies to support both of the above types of non-transformative technologies will often need to target specific technologies, for instance through subsidies for R&D or demonstration projects, but over time the means of support should become progressively more technology-neutral, such as a carbon tax. The inflection point for when policy should change from targeted support to a technology-neutral policy will be specific to each technology and also difficult to identify. Withdrawing targeted support too soon could kill a technology, whereas maintaining targeted support for too long would be both financially inefficient and possibly damage the development of other, potentially more effective technologies.

On-shore wind and biomass are incremental technologies that are competitive in niche markets. The price competitiveness of these technologies could be encouraged through market mechanisms, for instance through a carbon tax.

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Many energy efficiency measures and industrial combined heat and power (CHP) are incremental and already commercially viable, particularly where carbon taxes or emissions trading systems create a cost for greenhouse-gas emissions. Deployment is kept back by market and other barriers, such as building traditions and established user practices. Government support for this group should include specific measures to address information, market, legal, regulatory or financial barriers. For these types of technologies, the IEA recommends the following policies:

- "Regulatory or control mechanisms such as energy building codes or minimum energy performance standards for appliances through which governments can impose requirements to invest in energy-efficient technologies and infrastructure.
- Fiscal or tax policies through which governments offer consumers tax incentives for investment in energy-efficient technologies or procure energy-efficient technologies themselves.
- Promotion and market transformation programmes through which governments or energy providers influence consumers to purchase energy-efficient technologies.
- Financial remediation measures through which governments or energy providers offer special financing or lines of credit for energy-efficient technology investments.
- Commercial development and industry support mechanisms through which governments or energy providers partner with the private sector to increase the deployment of energy-efficient commercial buildings" (IEA, 2010, p. 469).

7.3 Transformative change

For transformations which alter economic structures (and in some cases with far reaching changes to society), we need a policy framework that can guide decisions over the long-term. These policies must also be able to adjust to changing circumstances. Long-term policies have fallen into disrepute after the 1970s, but the issue of long-term policy design is politically salient again (Voss et al., 2009). For instance, the European Commission has identified several major challenges which will require transformative change as they cannot be met through single measures and specific technologies. The major challenges are: climate change, aging populations, food security, and security of energy supply.[91]

The European Commission has introduced several policy instruments to address the major challenges. Many are based on a partnership model with existing industry, such as Joint Technology Initiatives (JTIs) and Public Private Partnerships to develop green cars, clean skies, innovative medicines, and factories of the future. Although useful in varying degrees, there is a danger that they draw on too narrow perspectives and rely too much on actors with an interest in the status quo and that the approach does not go beyond an innovation support approach. If they do, they will fail because they do not taken sufficiently into account three important issues of transformations.

First, transformative change implies a *destabilisation* of existing socio-technical structures. Similar to Schumpeter's concept of creative destruction, transformations result in major economic changes that will be resisted by actors who have something to lose (Smith and Stirling, 2010). Second, government *itself* is involved in the reproduction of existing socio-technical relationships through innovation policy. Examples include regulations that create market entry barriers and many direct and indirect subsidies that support existing economic systems. Third, transformative change is often (though not always) pioneered by *new actors*, whose standing in the policy arena is smaller than those of incumbents (Steward, 2008). These characteristics of transformative change suggest that policy instruments and goals must be independent of the interests of established actors so that there is ample room for new entrants and new ideas (Loorbach, 2007; Rotmans and Loorbach, 2009).

[91] Speech by European Commissioner Máire Geoghegan-Quinn at the opening of the European Research Area Board Conference (ERAB), Seville, May 6th 2010. The vehicle for dealing with the Grand Challenges are the 'European Research and Innovation Partnerships'. Their main ambition is to synchronise large-scale Research and Development efforts around the Grand Challenges. http://ec.europa.eu/research/erab/pdf/conference-speech_en.pdf.

In addition, transitions involve a great deal of uncertainty (Voss et al., 2009). Transformative change typically generates new unforeseen problems that need to be solved. Although not directly related to transformative changes, the biofuel experience provides an example. First generation biofuels based on using food crops to produce ethanol or bio-diesel created new problems for food security and possibly created more CO_2 than they saved, as a result of land use changes in developing countries.

Transformative changes should not be driven by a single perspective. The challenge for government is to take society into a new direction, which requires nurturing alternative systems and changing the framework conditions. To do so, government must concern itself with issues of orientation, coordination of private and public decision-making, and fostering learning and adaptation over an extended period. This requires decisions on where to go, the creation of institutions and mechanisms for transformative change, and choosing appropriate policies.

Where to go

The starting point for transition policy is to determine where to go. Transformations can be defined in very broad terms (such as a low-carbon society) and in more concrete terms.

A broader definition should include a *positive vision* that attracts the support of citizens and industry (Rotmans et al, 2001). Working longer is not an attractive option (at least for citizens) but working more efficiently in order to live longer and healthier lives is. Climate protection policies can be pursued as part of a quality of life strategy that will result in more pleasant and liveable urban environments. This requires integrating climate change actions with sustainable mobility strategies to co-optimise benefits. Integrated system analysis is needed to assess the viability of the vision and to separate public relations claims (greenwash) from real benefits.

At the more detailed, concrete level, **three major transitions** are required to address climate change:

1. Decarbonisation of electrical power generation and electrification of the transport sector.
2. Dematerialisation of the economy through energy efficient products (including homes) and re-use and recycling of products and waste.
3. Adaptation to the consequences of climate change

Decarbonisation of the power sector means a shift to zero-carbon technologies. Getting more usable energy out of fossil fuels is a necessary strategy for the short-term, such as through more efficient automobile, ship, and aircraft engines. Using waste heat is another strategy, practiced by two steel companies in the US, saving 190 MW of power in 2005 (Ayres and Ayres, 2009). In Europe there is an enormous waste of low temperature heat which can be used by business for producing electricity (as the steel companies did) and for heating/drying purposes.[92] Opportunities for the use of waste heat are enormous and far exceed the carbon reductions that can be achieved through low-carbon power, often at lower cost. Micro-cogeneration can be used to heat single homes and can be combined into virtual power stations.

Full decarbonisation can be achieved through several alternatives, including solar energy, wind power, geothermal energy, biomass, nuclear energy and possibly CCS, if it is cost-effective compared to alternatives. The optimum mix of energy sources will depend on natural endowments for these energy sources. Decarbonisation of the power sector implies a complete phase-out of fossil-fuel plants unless accompanied by CCS systems that can remove all carbon emissions. With a decarbonised power sector, greenhouse gas emissions from ground transport can be eliminated by shifting to electric propulsion using batteries and fuel cells. CO_2 emissions from shipping and air transport could be reduced by using advanced biofuels.

Dematerialisation consists of using less material, energy, water and land resources for the same economic output (Fischer-Kowalski and Swilling, 2011). Resource productivity is another name for it. Dematerialisation can be achieved through the use of light-weight products and from the re-use and recycling of waste products (called *re-*

[92] In Europe, total heat losses correspond to more than half of the total energy supply, indicating a great potential for heat recovery (Euroheat & Power (2006, p. 10). In 2007 in the Netherlands, cogeneration provides for 30% of heating needs and 50% of power consumption in industry, thanks to an active support policy. District heating is another way of using waste heat from combustion.

materialisation by Brigenzu and Bleischwitz, 2009). A useful and possibly achievable policy target is the doubling of resource productivity from 2010 to 2030. This would bring significant climate mitigation benefits.

Climate adaptation is a necessary strategy in addition to climate mitigation efforts. Given current CO_2 emission trajectories, the world is unlikely to avoid some degree of climate change (see Chapter 2) in the near future and dangerous climate change over the longer term. Climate change presents designers, architects and planners with the imperative to create or remodel outdoor spaces and buildings that are resilient in the face of future climate effects (Shaw et al., 2007), use less energy, and prevent heat stress and heat-related deaths. Agriculture has to adapt to a changing climate in order to ensure food supply and flood-prone settlements must be protected against flooding or moved out of danger.

Managing the global climate through geo-engineering is another strategy, although actions that improve the climate in one region could make the climate worse in another, creating international conflict. Geo-engineering could also have disastrous effects on the global climate. For both reasons, geo-engineering is controversial. Further research into its potential and risks is needed. There is also room for safe forms of geo-engineering such as bio-sequestering carbon or actively removing CO_2 from the atmosphere. The latter is currently far more expensive than preventing CO_2 emissions.

There are policies and supporters for each of these major transitions. Europe 2020 is an important policy initiative supporting renewables and energy saving. Climate change adaptation is increasingly a requirement of national planning and design guidance (Shaw et al. 2007). For instance, under the Strategic Environmental Assessment SEA Directive, land use planners are legally obliged to consider the future effects of climate change.

Getting more energy out of fossil fuels could be subsumed under dematerialization. Other labels could be devised to overcome cultural interpretations of words such as 'waste'. Perhaps we should not talk about waste but about secondary resources. We need new concepts (such as carbon rulers, negawatthours, zero-energy houses, smart grid systems, and climate-robust investments). A better world cannot be achieved on the basis of a single vision, as shown by the examples of scientific forestry in Germany, collectivisation of agriculture in Russia, forced villagisation in Tanzania and modern functionally separated cities that disappoint both economically and socially (Scott, 1998).

Creating institutions and mechanisms for transformative change

Transformative change requires mechanisms and institutions that sustain it. A clear commitment to achieving carbon reductions (such as the 60% reduction of carbon dioxide emissions stipulated in the Climate Bill in the UK) is one way of doing so. The rationale for having a clear long-term goal is that the realisation of long-term policy goals extends well beyond electoral cycles and management terms, even beyond a generation of civil servants (Voss et al., 2009. Yet a long-term goal that is written into law is not enough: institutions, mechanisms and policies must be created that can deliver progress towards the goal. As noted by Steward (2009, p. 16), "The nature of the innovation journey will be as critical as the destination".

At the national level, policy development tends to involve government in close relationship with a small number of leading national corporate businesses (Steward, 2009, p. 20). In situations where transformative change is required, the development of policy needs to draw on a much wider range of perspectives to ensure that it can support start-ups and entrepreneurial firms, broader organisational innovation, and social innovation.

The creation of partnerships for transformative changes (electric mobility, passive homes, etc.) is one way of doing so. The Dutch transition platforms for sustainable energy (See Box 7.1) are one possible model. Each platform had a chair, appointed by the government, and 10 to 15 members selected by the chair (Dietz et al. 2008). Platform members could chair temporary working groups that included a diverse range of experts, NGOs and entrepreneurs with the task of identifying relevant solutions and strategies for the platform. The use of temporary working groups expanded the number of involved experts to between 60 and 80 people, drawn from a diverse range of businesses and organisations (Dietz et al. 2008).

These types of platforms can advise governments on the types of technologies which should be funded and the types of policy instruments that could help achieve different goals. Support for a variety of alternatives at an early stage is a necessary strategy for escaping lock-in. The presence of feasible alternatives can overcome claims that 'radical change is impossible' and create first-movers that break with traditional solutions (Geels et al., 2010).

Given that a long-term policy for transformative change will involve a range of government bodies at various administrative levels, a capacity to coordinate policy intervention must be created (Jacobsson and Kemp, 2010).

Choosing appropriate policies

Creating policies to induce and guide social and technological innovations that are capable of replacing established ways of doing things is the third pillar of a transformation framework (Voss et al., 2009). The chosen policies need to provide both continuity and adaptability, requiring a delicate balancing act, and be mindful about indirect effects that create new problems in other areas. This requires interactive learning between policy and societal actors. The implication is that climate mitigation policy should not be pursued within a narrow strategy of promoting the use of renewable energy. Instead, the prevention of dangerous climate change should be pursued as part of a *broader sustainable development strategy*. The issue of which instruments should be chosen is examined in greater detail in the next section where we discuss twelve themes for policy and governance.

7.4 Twelve themes for innovation policy for climate protection

This section develops twelve themes for innovation policy for climate protection, drawing on the literature on innovation policy and the more specialised literature on eco-innovation and energy technology policy.

1) Integrating climate policy in green development and quality of life policies.
Climate change policy is best pursued within a green growth strategy and quality of life strategy, rather than as an environmental policy. Doing so helps to secure a wider range of benefits and may also be a more effective way of achieving greater climate protection benefits. Integrating climate policy in a green development strategy helps policy to focus more on the positive jobs aspects of climate protection which are significant, and may help to avoid investments that are harmful to the climate (the building of new coal-fired power plants without CCS for instance). Growth and quality of life are the two most important policy goals for which strong agendas exist. Integrating climate mitigation in those agendas thus makes sense from the viewpoint of effectiveness and may also fulfil the useful function of bringing together rather separate agendas.

2) Policies should be based on identified barriers and understanding of innovation dynamics
Policy should be based on identified barriers to innovation. This requires mechanisms for learning about those barriers and the long-time periods involved. Hype-disillusionment cycles must be avoided. Experience from Denmark and Germany during the 1990s highlighted the importance of long-term support for developing the potential of renewable energy technology (Jacobsson and Lauber 2006). Technology can fail because of the premature abandonment of support following disappointing results, a need to cut spending, or the introduction of market competition before a technology is ready (Verbong et al, 2008).

According to a study of the Wuppertal Institute for the European Parliament, the eco-innovation support programmes of the European Commission programmes suffer from three funding gaps: between R&D and the start-up phase, between the start-up and early stage, and between the early stage and mass market commercialisation (Figure 7.1). For a deeper analysis into barriers and gaps the model of innovation functions can be used to diagnose knowledge development, knowledge diffusion, resource mobilisation, research guidance, entrepreneurial activity, market development and legitimacy (societal support) for a specific technology innovation system (e.g. solar PV) within a nation (Hekkert et al., 2007; Bergek et al., 2008).

European Commission
Enterprise and Industry

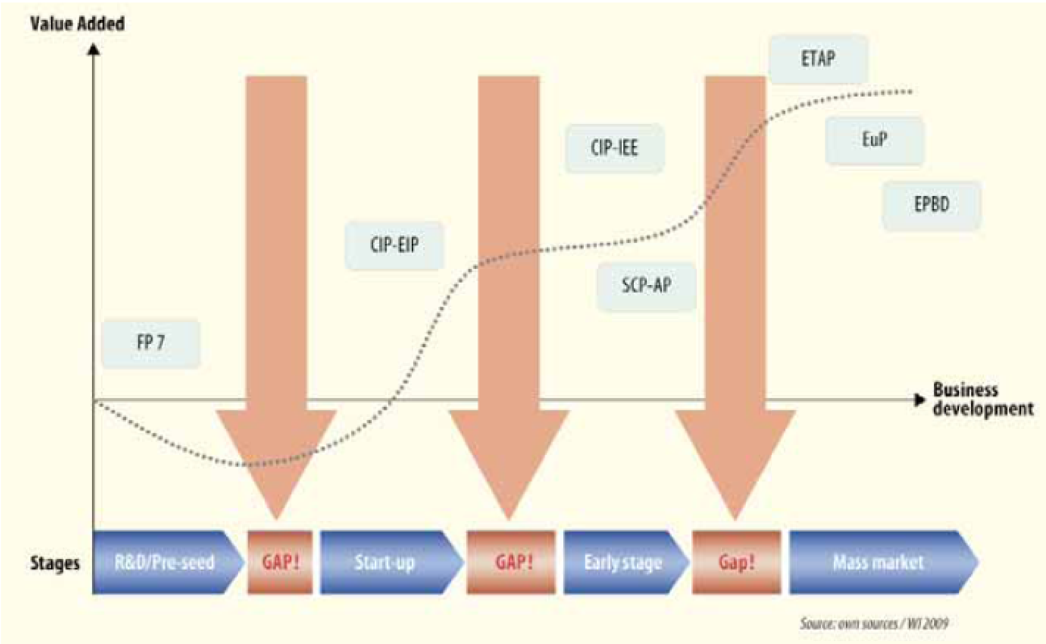

Figure 7.1 **Gaps of current EU programmes on eco-innovation**
Source: Bleischwitz et al. (2009, p. vi).

3) Avoid wasteful windfall profits

A danger with innovation support policies for low carbon technologies is that they can generate windfall profits. This consumes scarce resources that could be used on other projects and in some cases can actually prevent firms from investing in new technology.

One example is when firms would have invested in innovation in the absence of financial incentives to make such investments. Expert opinion can help to prevent this, but there is often no *ex ante* evidence that can be used to determine if support creates additionality (it creates more investment than would otherwise occur without the support).

Another example of windfall profits is due to the grandfathering of CO_2 rights in the first period of the European carbon emissions trading scheme (ETS). According to its 2009 financial report, steel manufacturer Arcelor Mittal earned 108 million Euros selling permits since 2007. The UK-based NGO Sandbag7 estimates that Arcelor Mittal will have around 100 million surplus allowances at the end of phase II of the ETS (2008-2012), with a value of close to 1.4 billion Euros. The French cement manufacturer Lafarge earned money from carbon emission rights that it got for free. In its 2009 financial report Lafarge states that it earned 142 million Euros, from the sale of carbon credits in 2009. The annual report also says that the freely allocated permits in 2010 will exceed their needs[93]. This will create no incentive to invest in low carbon cement. In 2010, the ETS was expected to have a large percentage of unused allowances (as in 2009) because of the economic slowdown. The unused allowances could be expected to delay investments in CO_2 reduction measures.

The ETS is an important system for achieving greenhouse gas reductions and should deliver more than it has done so far, once it is expanded to other sectors and allowances are steadily reduced. The ETS system can also be further improved. Provisions could be made for economic downturns. Auctioning of at least part of the permits for all sectors will help reduce windfall profits. From the start of the third trading period in 2013 half of the allowances will be auctioned. Some sectors such as the steel and cement industry will continue to received their allowances for

[93] http://www.corporateeurope.org/climate-and-energy/content/2010/05/industry-hits-carbon-leakage-jackpot

European Commission
Enterprise and Industry

free but the amount of allowances they will get will be reduced. This will help to reduce and ultimately eliminate windfall profits.

4) High level expertise for policy makers: independent climate change agency

Climate change policy needs to be developed in the public interest, which requires avoiding regulatory capture by parties with financial interests in the outcome and the ability to assess the accuracy of lobbying and promotional campaigns for favoured technologies and seeing through fashionable policy discourses. Every new EU policy is subjected to an impact assessment the results of which are being discussed with industry and other stakeholders (for example, environmental NGO). The details of the impact assessment is also being discussed with stakeholders which have quite an important influence on the way the assessment is done and the results from it, even when the study is being done by independent researchers. Political decision-making on issues surrounded with uncertainty (such as risks of carbon leakage) would benefit from an independent policy institution. An example is the independent regulatory agencies for pharmaceuticals, such as the Food and Drug Administration in the United States and the European Medical Evaluation Agency in Europe. Although neither of these two agencies is entirely immune to industry influence, they combine high levels of expertise with some independence from both government and industry.

Such an agency for climate change can assist policy makers at different government levels to deal with uncertainty and conflicting claims and evidence (Jacobsson and Kemp, 2010) and to assist the continuous long-term process of adaptive policymaking. Two types of expertise are required: 1) an analytical knowledge of the economics of innovation and the effect of policy instruments and 2) extensive knowledge of the technological options and the energy systems, including knowledge about strategic games and social acceptance. The latter covers regional, national, and continental level sources of zero carbon energy, systems for distributing the energy, consumer demand and preferences, etc. This type of competence requires both engineering expertise and knowledge from the social and behavioural sciences. This would aid a more realistic assessment of the potential for implementation of various low-carbon options and the carbon reductions that more realistically can be achieved. For example, the mitigation studies assessing GHG reduction possibilities reviewed in chapter 3 can be criticised for taking an overly economic viewpoint. There is a need to draw on social science for understanding consumer behaviour and company behaviour (how such behaviour depends on practices, mental models, cultural frames and individual circumstances which differ across places).

In addition, the sustainability, cost, reliability and other claims for different technologies need to be thoroughly assessed. A key prerequisite is an independent organisation responsible for Life Cycle Analysis (LCA) to assess and verify competing claims, for instance for the CO_2 footprint of different products and services (OECD, 2009). Such studies may help to increase the knowledge base and anticipate problems (such as biodiversity loss and higher food prices as a result of the production of biofuels) at an early stage. Decision makers must be able to draw upon independent research on the value of alternative technologies (Jacobsson and Kemp, 2010).

5) Specific versus general support

Targeted R&D support for specific technology has a poor reputation, on the assumption that "government cannot pick winners". An example is the failed policy support for synfuels in the 1970s.

Three things can be said about this. First, some form of targeted technology support is necessary for dealing with specific barriers to low-carbon technologies. In particular, radical and transformative technologies are unlikely to be developed in response to carbon prices alone. The risks for private firms are simply too high, requiring targeted public support to enable adequate investment in R&D (Hourihan and Atkinson, 2011).

Second, not all public support programmes fail, in the same way that not all private investments succeed. There are a number of successes, such as wind power in Denmark.

Third, innovation support is especially needed for the creation of radical innovations whose uncertainty, long-term payoff (because of long development time) and problems of appropriating the benefits amongst multiple contributors, work against their development. A recent study by leading innovation researchers into the role of government support in four important sectors (agriculture, chemicals, life sciences, and information technology) found that "In nearly every sector, federal policy has also been critically important in either stimulating or providing demand, particularly in the industry's early stages. Policies have also ensured that fundamental research has been simultaneously creative and useful – a balancing act that is notoriously hard to pull off – and in shaping the "rules of the game" to encourage competition and entry by new innovative firms" (Henderson and Newell, 2010, p. 2).

Given the importance of mitigating climate change, innovation policy needs to adopt a portfolio approach. Investment needs to be made in multiple technological options, accepting the fact that some will fail. In addition, policy needs to avoid focusing on low-risk projects (which are less in need of support). The purpose of government support is to encourage experimentation (Smits and Kuhlmann, 2005) and reduce risk through subsidising high-risk projects that the private sector is unwilling to undertake on its own.

Market pull through the use of generic instruments is not enough to bring forward radical innovations, as radical innovations have long development times and confront all kind of barriers. A market-based cap - and - trade system alone will not deliver emissions reductions and climate technology deployment at the scale and speed necessary for climate stabilization. Market-pull policies must be combined with additional policies to accelerate climate technology innovation nationally and internationally through more aggressive, creative, and collaborative research and product development (Milford and Morey, 2009).

6) Acting now or later?

An increasingly common argument that is addressed in Chapter 2 is that we should wait for cheaper low-carbon energy technology, using the next 10 years to bring down the costs through large investments in R&D – the 'R&D investment model'. As shown in Chapter 2, this option may have been feasible if actions to curb GHG emissions by 1.85% per year had begun in 2000. Due to the delay in serious action, preventing dangerous climate change would require economically painful cuts in emissions to begin today, which has the negative effect of strengthening the proponents of the R&D investment model in order to delay the pain.

In addition to the fact that we do not have 10 years to wait for zero carbon energy that is competitive with coal electrical generation, the R&D investment model is based on the fallacy that energy technology will fall considerably in price without widespread application. Innovation research, in contrast, shows that a large share of the expected cost decrease from a new technology is due to learning and incremental improvements, which depends on capacity and deployment. Low and zero energy technologies need to be introduced now or in the near future in order to gain experience that will reduce costs later.

Another reason to act now includes the time required for policy learning and adaptation. Perhaps most worrying of all, a delay of 10 years will result in the need for far greater annual declines in emissions. This would place sizeable strains on capital investment requirements (ECF, 2010). According to the Roadmap 2050, the costs of a 10 year delay in investment in low and zero carbon energy generation will require up to a doubling of annual investments above business as usual levels to obtain a 60% reduction in emissions (already not nearly enough), compared to a 34% increase in investments if action began in 2010 (ECF (2010).

7) New missions?

Among innovation experts there is a discussion of whether persistent problems such as global warming warrant mission-oriented programmes. According to Keith Smith, the answer is yes: "We now require new large-scale "mission-oriented" technology programs for low- or zero emissions energy carriers and technologies, resting on public sector coordination and taking a system-wide perspective" (Smith, 2008, p 2). Others are sceptical of the usefulness of missions. According to innovation experts Mowery, Nelson and Martin, global warming cannot be effectively dealt with through technology missions, because the challenge is not to develop technologies but to get innovations adopted, which is very much a matter of economics rather than technology. They do however believe that "strong, well-resourced government technology policy is part of the solution" (Mowery et al., 2010, p. 1012).

Superficially the attention to missions seems like a return to the emphasis in the 1950s and 1960s on public goals to guide science and technology development. There is however a big difference between the old missions

European Commission
Enterprise and Industry

and the new one for environmentally sustainable development: the older projects developed radically new technologies through government procurement projects that were largely isolated from the economy (Soete and Arundel, 1993, p. 51). Mission-oriented projects for sustainable development require the adoption of new technologies and practices across a wide range of sectors as well as changes in consumer demand and behaviour. This brings many actors into the process and will require a range of policies and customised solutions to deal with the many barriers.[94] Economic feasibility is a key condition, together with social acceptability. An overview of the difference between old and new mission policies is given in Table 7.1.

Table 7.1 Characteristics of Old and New "Mission-Oriented" Projects

Old: Defence, Nuclear and Aerospace	New: Environmental Technologies
The mission is defined in terms of the number of technical achievements with little regard to their economic feasibility	The mission is defined in terms of economically feasible technical solutions to particular environmental problems.
The goals and the direction of technological development are defined in advance by a small group of experts	The direction of technical change is influenced by a wide range of actors including the government, private firms and consumer groups
Centralised control within a government administration	Decentralised control with a large number of involved agents
Diffusion of results outside the core of participants is of minor importance or actively discouraged	Diffusion of the results is a central goals and is actively encouraged
Limited to a small group of firms that can participate owing to the emphasis on a small number of radical technologies	An emphasis on the incrementalist development of both radical and incremental innovations in order to permit a large number of firms to participate
Self-contained projects with little need for complementary policies and scant attention paid to coherence	Complementary policies vital for success and close attention paid to coherence with other goals

Source: Soete and Arundel (1993, p. 51)

Spending more on energy R&D to bring down the costs of low-carbon technologies is part of the solution, but this will help to deal with only one barrier, which is cost. We disagree with the conclusion of Pacala and Socolow (2004) that cost is the major barrier, which can be managed through early and massive investment in R&D.

We would argue that there is a role for technology development missions *and* a role for diffusion oriented missions. A technology development mission is needed for car batteries and electric mobility. Current electric cars use batteries designed for laptops. The availability of less expensive batteries with better performance than lithium-ion batteries is necessary for the electrification of the transport sector. We also need mission policies for sustainable mobility aimed at achieving a modal shift with a greater role for non-motorised transport. This is a mission of transformative innovation, with an important role for road pricing, an innovation to be introduced in society strategically. Here the innovation challenge is one of clever implementation using configurations that are socially and politically possible. Lessons should be disseminated.

A technological mission which receives a great deal of attention is the Desertec project. The goal is to supply 15% of Europe's power by 2050, by implementing concentrated solar power (CSP) systems in the Sahara Desert and Middle-East and transmitting the electricity to Europe by a super grid of high-voltage direct current cables. The concept was initially developed by the Trans-Mediterranean Renewable Energy Cooperation and the Club of Rome. In 2009, an industrial consortium was created to design and implement the project. The project is estimated to cost about Euros 400 billion.[95] Many things have been said about this project. Herman Scheer, an expert on renewable energy, considers it unnecessary in view of the potential for renewable energy in Europe and others feel it creates

[94] Dealing with barriers is not just an issue of the user context adapting to technological possibilities but also of finding suitable solutions for the local context.

[95] From http://www.greeneconomycoalition.org/node/24

undesirable energy dependency. Without going into the validity of those arguments, there is a simpler option here. One could start a Desertec in European countries such as Spain and Southern Italy and learn about different configurations. It would be wise to first test different technologies before embarking on major irreversible investments.

One of the dangers of mission-oriented energy projects is that they could be uneconomic in the long-term (fusion power is an example, with no commercial potential after 40 years of investment). A requirement of co-funding by industry is one way of making sure that the technologies to be developed will not turn out to be "white elephants" or "cathedrals in the desert" (von Tunzelmann and Nassehi, 2004), as long as there is a mechanisms to ensure that projects without the support of major industrial companies can also be funded. A possible option is the public-private partnership model that is used in the German *Clean Energy Partnership* (CEP) for hydrogen and fuel cell vehicles, which was instrumental in the creation of the German *National Innovation Programme Hydrogen and Fuel Cell Technology* (NIP). For transport applications 700 million Euros are available to pay for HFCV research and innovation projects for the 2007-2016 period, with half of this sum coming from industry. A *National Development Plan* (NEP) specifies the agenda for technology development. To coordinate policy goals and implement projects, a quasi-governmental organization was set up: the *National Organization Hydrogen and Fuel Cell Technology* (NOW). NOW participates in all steering committee meetings and ensures that political imperatives are respected. NOW also makes sure CEP is aligned with related R&D and demonstration activities in Germany. Alignment of German activities with those abroad is achieved through international contacts with related organizations such as the EU *Fuel Cells and Hydrogen - Joint Undertaking* (Ehret and Dignum, 2010). It is entirely possible of course that the market for FCV will be small and that the HFCV will be a white elephant, which is why we need *multiple* technology innovation mission programmes, a point further developed below.

The model of strategic niche management (Kemp et al., 1998; Hoogma et al., 2002) can also help to guide policy. SNM aims to speed the commercialisation of new technologies by encouraging their use by real users in selected niches. The niches consist of applications in which the technology or innovation is already attractive due to specific circumstances (a local problem or the availability of specific resources). Experiences in the niche are then used to inform decisions about technical improvement and support policies, aimed at expanding the original niche and making a transition towards a more sustainable system. The protected space, in which the technology is temporarily protected from the full force of normal selection pressures, acts as a test bed and incubator for the new technology. It may pave the way for private and government support policies in a gradual, non-distortionary, and thus *doable* way (Kemp et al., 2000). SNM policies are unlikely to bring about a transformation of their own (Smith, 2007; Courvisanos, 2009). They are useful for preparing public investments and the setting of environmental standards which will be needed to change unsustainable practices.

8) Policy coordination

There is a pressing need for policy coordination across the EU, partly to ensure the effectiveness of publicly funded research and to reduce replication, partly to create sufficient demand, and partly to encourage international and domestic cooperation. While R&D policy can help facilitate the creation of new environmentally friendly technologies, it provides little incentive to adopt these technologies (Newell, 2010, p. 263). Adoption calls for demand-side measures but the incentives for innovation from politically possible market pull policies may be too weak or unduly favour particular types of technologies (Jacobsson et al., 2009; Kemp and Pontoglio, 2008).

Coordination is particularly important within the EU because renewable energy sources are not equally distributed across the EU. Some countries such as the UK and Ireland have ample wind power reserves while others such as Spain have excellent sites for solar power. Other countries have fewer renewable energy possibilities (reflected in the country-specific targets for renewable energy in the EU's Climate and energy package[96]) and will need to rely either on power from other regions (requiring an EU-wide smart electrical grid) or on nuclear power. The coordina-

[96] National targets range from a renewables share of 10% in Malta to 49% in Sweden.
http://ec.europa.eu/clima/policies/brief/eu/package_en.htm

tion role needs to be managed by the European Commission, as the only organisation that can coordinate national efforts. Furthermore, the EC needs to set strong, credible policy commitments to encourage large scale investment by private firms. For this also the implementation of respective policies in the Member States is of great importance. This includes the provision and stability[97] of support mechanisms (like feed-in tariffs or quota schemes) as well as the removal of non-economic barriers.

For transformative innovation, policy coordination is needed across sectors and levels of government. The focus for achieving CO_2 reductions in transport is on electric vehicles powered by batteries and fuel cells. CO_2 reductions can also be achieved through policies to *reduce* car-based mobility, through improved public transport, organised car sharing and integrated transport. Intermodal travel is a niche phenomenon both in terms of use and in terms of a lack of a developed knowledge infrastructure. There are few spokesmen for it and a limited amount of technical and professional cohesion is evident from best practice publications. A study about intermodal travel in the Netherlands and UK learned that policy interest is unstable and often implicit; in the UK the whole ethos of promoting intermodality did not fit well with the dominant political hegemony of 'allowing the market to decide' (Parkhurst et al., 2010). As a result, both rail and bus-related initiatives have generally remained piecemeal, tentative and over-dependent on local factors, such as the presence of policy entrepreneurs or particular coalitions of actors (Parkhurst et al., 2010).

The experiences in the Netherlands and the UK suggest that transport intermodality will rarely emerge as a significant phenomenon without national government support and coordination from willing actors (which cannot be assumed). Even in the Netherlands, where transport coordination is more possible, major organizational barriers exist, such as the fragmented systems of mobility providers and public transport concessions. To overcome these barriers and promote sustainable mobility, a long-term coordinated approach is necessary to implement convenient car-public transport interchanges, bicycles for short-term rental that are integrated with public transport; integrated ticketing across different transport modes; dynamic information and booking services, and individualized demand-responsive forms of public transport that provide links to scheduled public transport (from Parkhurst et al., 2010).

9) Strategic intelligence for innovation

The choice and selection of innovation projects requires strategic intelligence (Smits and Kuhlmann, 2002; 2005). In the report *Towards a 50% more efficient road transport system by 2030,* the European Road Transport Research Advisory Council analyses how the transport sector can be made more energy-efficient, cut carbon emissions, and improve safety, reliability and efficiency. Innovation policy can build on such recommendations and assist in the creation of strategic intelligence. There is a need for strategic intelligence for smart grids, a broad concept comprising a multitude of options, to investigate benefits and viability of configurations. There is a need for critical assessment of societal benefits (including benefits in climate mitigation) because smart grids are very much 'talked up' by those interested in it. Electric mobility is another candidate for the creation of strategic intelligence, being a critical innovation for climate protection. Strategic intelligence may also be created for social innovations, such as product sharing.

10) R&D support

A broad range of options for climate mitigation needs to be supported – all low and zero carbon energy technology needs to be further developed. Otherwise, the EU will find it very difficult if not impossible to reduce emissions to 1 tonne per person by 2050, or to even meet less ambitious goals of a 50% decline in emissions by 2050 (IEA, 2010). It is especially important that disruptive and radical technologies are also supported and not just options which help to make present systems greener (it is equally important that one does not rely too strongly on long-term solutions

[97] One lesson from the support schemes for renewable energy investment is that the costs of support should be borne by energy consumers rather than tax payers to avoid stop-start interruptions when government budgets become more constrained (COM(2011) 31 final, p. 9).

as they may remain a long-term solution, nuclear fusion being an example of this). This involves funding blue-sky exploratory research into a diversified portfolio of research projects.

Unfortunately, the global financial crisis has diverted the EC's SET Plan for more R&D to a greater focus on regulations and market mechanisms for pricing emissions (David, 2009). Pricing mechanisms are unlikely to be sufficient, with extensive public R&D necessary. In any case, the SET Plan was not ambitious enough, proposing annual expenditures of 7.5 billion Euros in R&D support from the private and public sector combined, when the public sector should be contributing between 5 and 11 billion Euros per year alone.

Public funds might be used more efficiently by exploring alternative funding mechanisms. Grant funding can result in high government costs with no benefits (Adler, 2009). An additional problem is 'capture' of the grants system by industries that are only interested in short-term incremental solutions that promote their own technology (coal for instance). Public funding for marginal improvements (such as energy efficiency improvements of existing technologies) is a waste of public money, which should focus on technological frontiers and give special support to technologies from non-incumbents. Improving coal technologies should be funded by the private sector in response to carbon prices.

An alternative funding mechanism that could be explored is the use of prizes (OECD, 2010). Prizes encourage researchers to focus on a goal and are therefore suitable when a "goal can be defined in concrete terms, but the means of achieving that goal are too speculative to be reasonable for a traditional research program or procurement" (Kalil, 2006). In respect to zero carbon energy, the goal is often well known. To work, prizes need to be specific enough to ensure that the innovation is worth the investment, but flexible in how the goal is achieved. The problem is determining the size of the prize, to optimize private investment while minimizing the cost to the public purse. Adler (2009) notes that properly constructed "prizes have a peculiar virtue of imposing costs only to the extent that they produce results, so there is room to be ambitious".

11) Policy learning

Uncertainty as to the effects of policy instruments call for policy learning (Nauwelaers and Wintjes, 2008). Official research-based evaluations play a limited role in innovation policy, as policy instruments are seldom evaluated for their effectiveness and efficiency (Wintjes and Nauwelaers, 2008). Lessons learned by executive agencies and evaluators should be disseminated internationally. For transition it is important that policy learning evolves with the development of new technology innovation systems (Kemp and Loorbach, 2006). The Dutch energy transition approach (Box 7.1) was a useful model in this respect.

Box 7.1 The Dutch energy transition approach to move to a low-carbon energy system

An interesting attempt towards an energy transition is the Dutch transition approach to achieve a low-carbon economy. The approach focused on transformative change, bottom-up processes and the participation of business and other non-state actors. It grew out of deliberations between innovation researchers and policy makers in 2000. Policy makers accepted that a traditional policy approach based on short-term goals formulated by various ministries (in a non-coordinated way) would not work for fostering radical innovation. A different approach was needed that would address possibilities and barriers, draw on ideas for innovative change from market actors and innovative thinkers, with policy aligned to identified transition paths.

At the heart of the energy transition project were the activities of seven "transition platforms": new gas, green resources, chain efficiency, sustainable electricity supply, sustainable mobility, built environment and energy-producing greenhouses. For each platform, individuals from the private and public sector, academia and civil society jointly identified innovative system configurations, developed a goal for energy use or energy conversion, thought of pathways and programmes, and suggested transition experiments.

In total, 31 transition paths were selected, consisting of technologies at different states of development. The choice was based on technologies for which there was expertise in the Netherlands and an interest from businesses

European Commission
Enterprise and Industry

to work on them.

A transition action plan was formulated in 2006 with the following goals:

- A 50% reduction in CO_2 emissions by 2050 in a growing economy
- An increase in the rate of energy saving to 1.5- 2% a year
- A progressively more sustainable energy system
- The creation of new businesses

Any energy transition involves government agencies on different issues and at different levels. Some mechanism of cooperation is thus needed. In the Netherlands special arrangements were set up for this task, the most important of which was the Interdepartmental Project directorate Energy transition (IPE) The IPE plays an important role in taking initiatives, connecting and strengthening initiatives, evaluating existing policy and acting upon policy advice from the Regieorgaan and transition platforms. The goal was to stimulate interdepartmental coordination and to make the overall transition approach more coherent (UIPE, 2008, p. 10).

In drawing upon suggestions from the platforms, there was a danger of the transition process becoming a closed shop. Options outside the portfolio were disadvantaged but not locked out. New initiatives could emerge outside the platforms through parliament or because powerful parties in society were able to secure policy support for it. This happened in the case of battery electric vehicles for which a coalition of NGOs, business (Essent, Better Place), finance (ING, Rabo) and the Urgenda (a coalition for sustainability action) successfully lobbied Ministers and parliament to give special support to Battery Electric Vehicles (BEVs).

On the whole, policy coordination improved between 2004 and 2010. For example, BEVs, hybrid electric vehicles and other types of low-emission vehicles were subject to special fiscal treatment. There was more co-operation between Ministries and between government, business, research and civil society and also more co-operation between national and regional initiatives.

The Dutch transition approach created various kinds of capabilities for technologies and policy. The capability of government to act for systemic change was improved and there was a commitment to transitional change. This commitment is missing in many countries, where the political discussion on low-carbon energy is narrowly focused on centralised choices of CCS, natural gas power plants and nuclear energy. In the Netherlands, such discussions also take place, but the energy transition approach supports a broader set of options.

The Dutch approach was not without faults. The platforms were dominated by well-known energy companies (insider-outsider problem) (Kern and Smith, 2008). A second problem is that subsidies for energy investment were funded through general taxes, which makes those subsidies vulnerable to cuts. It is better to fund these through energy bills, as done in Germany, so as to create an element of continuity in energy transition policy. Dutch green energy policies were characterised by major discontinuities, which were harmful for energy innovation (Verbong et al., 2008). This is not specifically the fault of the energy transition approach, but the problem was not remedied (Kemp, 2010).

In 2010 the approach was officially abandoned by the new conservative government, partly for financial reasons and partly for ideological reasons (of leaving energy choices to the market).

12) International policy and local policy to complement EU and national policy

GHG emissions need to decline substantially around the world by 2050. Currently, 80% of the global population lives in countries where per capita emissions of CO_2 are above the sustainable level of 1 tonne per person.

International obligations for reducing carbon emissions are needed for creating a level playing field and for preventing carbon leakage. Obligations are best combined with the use of a carbon tax at the level of the EU and trading blocks as this will generate funds for research and for helping developing countries to develop and implement zero carbon technology. Such support is warranted on the grounds that developing countries do not have the resources to pay for low-carbon energy technologies and infrastructures; as small emitters of CO_2 they are also not responsible for global warming.

Substantial sums of capital must be transferred to developing countries to assist in the construction of zero carbon energy sources and infrastructure and to pay for the preservation of existing carbon sinks such as tropical forests and undisturbed savannah soils. Past programmes have been too small and resulted in minimal gains (for example the CDM mechanism). Adequate funds could be raised by an earmarked carbon tax, with all tax receipts transferred to developing countries.

The money from a carbon tax or from pooling resources may also be used to fund collaborative research into low-carbon technologies and to support multi-billion innovation programmes (Milford and Morey, 2009). Consortia of companies, public sector actors (cities for instance) and civil society groups could apply for sums. Such a system exists already in the EU but can be expanded within and beyond the EU.

To avoid carbon leakage and prod non-Annex 1 countries into climate action, an import tax on the carbon content imports will be very useful. WTO rules should be adapted to make this possible.

Policies at different levels should be made to work better with one another. Effective governance requires assigning the functions of government to the institutions that have the necessary leverage and accountability (Victor et al., 2005). Both the US constitution and the EU constitution are based on this (with the EU constitution also been based on redistribution). The diversity of Europe could be exploited to greater effect in terms of generating lessons about policy instruments and institutional change for low-carbon activities. The EU is demonstrating leadership with regard to climate change, the aging population, energy security and resource efficiency as grand challenges. To meet these challenges the EU is using the open method of coordination (OMC). The OMC's emphasis on learning, technological co-orientation and co-ordinated transfers, and on network structures of governance, may help to mobilise multi-level (international, national, regional) resources for climate policies. In the roadmap 2050 for moving to a competitive low-carbon economy in 2050[98], the EU asks Member States to develop national low carbon Roadmaps (vertical coordination). The Commission intends to use the Roadmap for developing sector specific policy initiatives and the 2050 energy Roadmap and the upcoming White Paper on Transport policy (horizontal coordination). Resource use is getting attention through the flagship initiative A Resource Efficient Europe. Many initiatives are foreseen in 2011 such as the European Energy Efficiency Plan 2020, the Communication on a 2020 EU biodiversity policy and strategy, Revision of the Energy Taxation Directive, Roadmap for a resource–efficient Europe, TEN-T revision and Energy Roadmap 2050.[99] With these initiatives the EU is on a good track. The challenge is to achieve results on the ground. For this the cooperation of many actors (especially local actors) has to be secured, both within Europe and outside Europe. With other countries engaging in climate policy, Europe can move much faster in the direction of a low-carbon economy because there will be less competitive disadvantages for energy-intensive sectors and faster progress in low-carbon technologies. The EU should use its economic power to this end and diplomacy. Internally, it may want to involve DG Development in climate policy.

7.5 What is not well understood or neglected

Several issues have been inadequately addressed in current research on climate change mitigation policies: behavioural change, dematerialisation, policy coordination and avoiding lock-in to suboptimal solutions.

Individual behaviour is an important issue. Stern (2002) noted that "if policies are to influence energy consumption more effectively, they need to reflect a more complex understanding of the many factors that shape or drive individual behaviours. Such policies will reflect not only the influence of financial costs and rewards and the availability of technology choices, but also the importance of personal capabilities, habits, values, norms and social and institutional contexts" (IEA, 2010, p. 599). What is lacking is a theory or integrated framework for behavioural change. The transition framework offers such a dynamic framework which not only endogenises behaviour but also company investments and government policy.

[98] COM(2011) 112 final.
[99] COM(2011) 21 final.

European Commission
Enterprise and Industry

Another issue that is not well worked out is the issue of critical materials for low-carbon technologies. As noted in Chapter 5 of this report, lithium-ion batteries for cars use cobalt, PV panels use indium and gallium, wind turbines use neodymium, fuel cells require platinum, and micro-capacitors for electric cars require niobium and tantalum– all 'critical materials' whose availability is limited. Resource availability constrain fossil fuel alternatives if the alternative relies on scarce resources. The policy implications of the critical materials issue for emerging low-carbon energy technologies are less clear than they may appear. On the one hand, we can expect market forces to bring forward substitutes, but given the large investments and time needed for search activities it is unclear whether this will happen in time. There is also a danger that market-based processes will produce a too narrow range of alternatives. The academic literature disagrees on whether resource scarcity or competition for scarce resources presents a fundamental problem or is easily solved by the market (UNEP, 2010, p. 8). In our mind, public support of research into alternatives is warranted to widen the search for substitute materials and speed up the time by which they are available. Another solution is to stimulate recycling of critical materials.

Material science appears highly relevant for climate mitigation. Nano-science and technology can be used to create special materials whose use could help to reduce fossil fuel energy use and reduce carbon emissions either directly or indirectly. Examples are carbon nanofiber cars and organic solar cells in which nano-particles increase their energy efficiency. Further research is needed, whether more funding for nanomaterials is needed or not.[100]

Alternatively, the solution may lie not in new materials but in a real *dematerialisation* strategy, aimed at reducing the material input per unit of service (Hinterberger and Schmidt-Bleek, 1999; Schmidt-Bleek, 2009) and increasing the amount of available energy per unit of primary energy (Ayres and Ayres, 2010). There are enormous opportunities for this. Ayres and Ayres (2010, p. 7) state that we can accomplish significant parts of this transition at a negative cost: simultaneously reducing energy costs, fuel use and greenhouse emissions. It avoids capital costs for building new nuclear or coal-fired power plants and oil-drilling platforms.

Public-private partnerships are often described as particularly suitable for innovation. Whereas there are clear advantages of mutual learning and pooling resources, as in the CEP programme for fuel cells, there are also disadvantages. They can delay far reaching change by serving incumbents rather than challengers, as in the auto-oil programme for clean air, which did nothing to promote electric vehicles.

7.6 Main policy conclusions

The basic IPAT equation that is discussed in Chapter 2 shows that emissions are a function of population, affluence and technology. Substantial technological improvement is the only solution to dangerous climate change that does require either a fall in affluence (at least affluence measured in the consumption of materials) or a fall in population. The latter is likely within Europe, due to below replacement birth rates, if immigration is constrained. However, this approach is unlikely to be feasible without significant increases in the retirement age that could be more unpopular than other actions to reduce emissions. Therefore, the primary approach to reducing emissions must be based on technological and organisational changes, which places innovation at the forefront of all policies to prevent dangerous climate change. This is not to exclude entirely changes in affluence and population, but changes in these two factors can only account for a small share of emission reductions.

The current EU policy is to reduce GHG emission by 20% below 1990 levels by 2020. To meet the 20% goal, energy CO_2 emissions would need to fall by 1.5% per year, which is only 0.5% above the current rate of decline. The 30% goal is more challenging, requiring a 2.8% decline in emissions, but both are well below the required rate of decline of 5.1%, using the simple equity principle and assuming that it is possible to 'buy' emission permits from low-emitting countries.

[100] In contrast, A Friends of the Earth report casts a very critical eye on nanotechnology, pointing to high energy use during production, health risks, and a failure to meet high promises (Friends of the Earth, 2010).

Effectively, these targets delay serious action on global warming until after 2020. There is a danger that delayed action won't reduce GHG emissions to a sustainable level because of supply constraints and demand constraints. Transitions take decades and sustained efforts. Sustainability transitions can be expected to take several decades longer. Research may bring the costs of low-carbon technologies down but learning curves also depend on time and capacity. Achieving a reduction of 80% in three instead of four decades may be not possible, nor inexpensive in view of capacity constraints.

Renewable technology cannot take the place of fossil fuels in the short term because of higher costs and planning contraints and neither can nuclear because it can take 10 years for a new nuclear plant to come into operation in Europe. Given that CCS is also not a short term option, over the short term policy should focus vigorously on energy efficiency. This particularly applies to space heating for residential and commercial buildings, which account for approximately 28% of EU emissions.[101] The inevitable increase in the share of the European population in older age cohorts will also increase residential demand for space heating and electrical power and possibly increase total energy demand, as described in Chapter 4. The importance of residential and commercial demand in combination with demographic change means that building regulations need to change quickly. In Europe, Zero energy houses must rapidly become the standard and be actively promoted not only through subsidies but also through regulation, forcing builders and architects to change course. Stringent CO_2 standards for new vehicles are also required to promote energy efficient internal combustion cars. Fleet standards for CO_2 per km can provide for necessary flexibility, but the long-term goal should be clear and upheld. Penalties in case of not meeting the standards would be desirable. Prolongation of nuclear plants is another option, attractive to utilities because there are no depreciation costs and dismantling costs will be postponed.

In the absence of CCS for achieving CO_2 reductions in the next decade, we need to simply use less fossil fuels and this requires carbon constraining policies and mechanisms to prevent rebound effects. In our view this should be a clear goal for policy. It will render obsolete the building of long-lived new power plants (WWF, 2009). New investments in coal fired plants or the prolongation of the life of coal plants are entirely inconsistent with a CO_2 reduction policy and should be avoided. Gas may substitute for coal until CCS or renewables are available. Clearly, what should *not* be done is to subsidise the use of fossil fuels. Giving away carbon emission rights for free to energy intensive sectors also undermines a climate strategy. In allocating emission rights national governments as well as the European Commission are under pressure by energy-intensive industries to provide those rights for free. Carbon leakage and loss of competitiveness are given as reasons for grandfathering CO_2 rights. Windfall profits from giving out too many carbon rights to companies can be avoided by reducing the number of rights that are given for free, thus making sure that at least some of the carbon rights must be bought (as will be the case from 2013 on). Another strategy is to tax profits from carbon trading.

Significant increases in electrical production and electrical transmission capacity are needed, both to manage renewable energy sources of electricity and an increase in demand for electricity to supply an all-electric transportation system According to ECF (2010), several thousands of kilometres of new inter-regional transmission infrastructure are required. The overall expansion required over 40 years is a factor-three increase from today's level of inter-regional transmission capacity (ECF, 2010, volume 1, p.14). This is not so much an innovation policy issue but an EU energy policy issue that is important for renewables and for achieving GHG reductions. A strategic interconnection plan based on minimising resource costs of decarbonisation across Europe is required (ECF, 2010, volume 2, p.30). Member states should ensure that the wholesale market framework and internal infrastructure will enable investors to take advantage of the import/export opportunities afforded by the strategic interconnection plan. They should also mandate network regulators within the framework of the internal energy market to create a robust investment framework enabling the necessary upgrade and roll-out of smart infrastructures at the transmission and distribution level (ECF, 2010, volume 2, p.30).

[101] This can be estimated from the direct emissions of these two sectors in Figure 2.3 of Chapter 2.

Given that climate mitigation will cost money, sustainable sources for funding need to be created. Possible sources of funding are: carbon auction revenues, carbon taxes and network system charges (ECF, 2010, volume 2, p. 31). Government may also underwrite key risks to reduce the overall financing costs for major projects (being a high risk strategy as risk transfers from investors to taxpayers often obscure associated hazards and hidden costs) (ECF, 2010, volume 2, p. 31). Spending should be sustainable, in the sense that the support can be continued for a long enough period to prevent busts from policy discontinuation. The preservation of major sinks (tropical forests) is also something where the EU could take some financial responsibility.

Younger European generations will need to bear more of the economic and social adjustment to a low GHG economy than older generations, even though they were less responsible for the problem. It would therefore be equitable to introduce policies that tax older cohorts at a higher rate for GHG emissions, or, at the minimum to reduce their per capita emissions to no more than that of younger age cohorts. Alternatively, older age cohorts could pay supplementary taxes to fund R&D into low emission energy technologies.

Climate change benefits can also be achieved through the use of other policies, especially resource efficiency policies as part of a strategy of dematerialisation. Resource efficiency will produce a range of benefits in the form of energy savings and reduced GHG emissions. In Germany, materials that are potentially recyclable account for an energy demand of 3600 PJ, whereas (currently) non-recyclable products are responsible for an energy consumption of 2000 PJ (figures for year 2000) – suggesting a large *technical* potential for energy saving through recycling (Nathani, 2006). There are also substantial opportunities in Europe to reduce emissions through land use changes that provide carbon sinks (McKinsey, 2009).

Climate policy might be able to piggy back on other issues, such as energy security, clean air policy, resource decoupling, transport policy (the promotion of cycling, congestion charging), dematerialisation (resource efficiency) policy, industrial policy etc., but non-climate policies may also erect barriers for it through the protection of national energy-intensive industries, coal industries and the car industry as well as the facilitation of car-mobility.

An important conclusion is that different innovations require different approaches. Markets appear quite capable of fostering incremental innovation. For radical and transformative innovation special support from government is needed. There is a need for generic policies and specific policies. Policy should not be viewed purely in instrumental terms but as a trajectory in itself. It may take 10 years or more before policies deliver substantial emission reductions, something which is absent in the discussion of climate policy. It is better to anticipate higher oil prices and to act on that now, given that energy systems are slow to change. Within 10 years time, all new buildings should be zero or very low energy buildings, reducing the need for natural gas, new investments in power generation should be climate-friendly and we should move from a waste society to a recycling economy (in which not only materials are recycled but also waste heat is used). Such changes do not require innovations new to the world, but simply political choice.

There is also a need to sensitise society to the need for carbon constraints. Innovation can alleviate tradeoffs but not dissolve these altogether. Policy should be involved in system change and make clear choices for where to go. Different nations will want to make different choices. The diversity across the EU can be usefully exploited. A country such as Germany can be at the forefront of every low-carbon energy development, but smaller countries and less rich countries can't. There is a need for EU money to help smaller countries. How to do this needs to be worked out.

The EU may want to reconsider its research and innovation policy. There is a need to fund research into adaptation and geo-engineering and to re-assess the SET-plan, which is dominated by plans from old businesses rather than those from new businesses. The money allocated to innovation in energy efficiency appears low in view of the challenge. There needs to be a better mechanism for deciding about such matters, there is too great a reliance on proposals from industry and research representing vested interests. More support should be given to transformative innovation, something which requires long-term policy and a good deal of policy coordination. With its new mandate for innovation, DG Research and Innovation is in a position to coordinate its research policy with its policy for innovation, but transformations cannot be achieved through a push approach alone; innovators that exceed energy performance standards and other standards should also be rewarded through market-linked mechanisms such as public procurement or low-interest loans in the case of zero-energy and positive energy buildings. The challenge is to define a dynamic mechanism for innovation diffusion and innovation development. The stimulation of both requires a set of coordinated policies.

There is also the wider international context. By being a frontrunner in climate policy there will be trade gains for low-carbon products and trade disadvantages for energy intensive business. Protecting the latter is at the disadvantage of the first. It is a matter of politics to strike a balance. In doing so, policy makers should take into account that demand for passive homes, climate adaptation, sustainable mobility, cities that are nice to live in, can be anticipated to grow in many parts of the world. Climate-safe innovations producing sustainability benefits are thus future proof: resource-intensive production is not.

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Appendix A. Climate change related scenarios and roadmaps

Scenario (Years covered; main focus)	Eventual percentage decline in GHGs	Policies for 2020, 2030 or 2050	Immediate reduction targets	Behavioural or organisational issues	Problem of transitions	Rebound problem	Additional R&D for low carbon technologies	Price on carbon	Technology-economy conclusions / Economic indicators
Giljum and Polzin (2009) To 2020 Decoupling economic activity from energy and resource use	EU CO_2 emissions 11% lower by 2020 than in 2005	All policies for the immediate future; Examples: improving resource efficiency, e.g. through establishment of "Resource Efficiency Agencies" advising firms, and by implementing resource accounting systems for firms and industries; rebound effect has to be taken into account	No specific target, but scenario implemented immediately	-	-	Policies should aim at increasing the prices for raw materials, e.g. through energy or material taxes or cap and trade systems	Additional business R&D should be subsidised with a total of 1% of public consumption, financed by a corresponding reduction in public consumption	Yes, 'significant tax' on CO_2	Integrated sustainability scenario vs. Baseline scenario: EU resource efficiency 13% higher, real GDP 4% higher and employment 0.2% higher in 2020 in the sustainability scenario.
National Intelligence Council (2008) To 2025 One of the four included scenarios related to climate change, focusing on a "post-petroleum age"	Any 'drastic cuts' by 2025 would probably cause economic havoc for the world	-	No target	Political will may not exist to reshape the international system to offer the emerging powers enough responsibility for them to shoulder more global burdens. In response to this and other likely deficits in global governance, networks will form among states and nonstate actors focused on specific issues, with non-state actors being relatively strong by 2025	Energy system transition will be smoother if PV and wind power and battery technology developed enough by then (fewer infrastructure changes); Technologies have long lead times - historically, there has been an adoption lag of 25 years for major technologies	-	-	-	Renewable energy sources are a not a large-scale viable option by 2025; Current technologies are inadequate for the scale required, and new possible energy technologies (energy storage, clean coal, coal gasification and biofuels) will take time; Natural gas and nuclear potential winners by 2025
Worldwatch Institute and the Fletcher School (2009) To 2030 Global transformational scenario: low carbon future with energy efficiency and renewables; focusing also on the many synergies between energy efficiency and renewables	Energy related CO_2 emissions in 2030 34% below 1990 levels, being on track for a necessary 80% reduction in total GHGs by 2050; 50% of global *primary* energy from renewables by 2030, with increasing proportion of the total as electricity, as heat and transportation sectors become more electrified, this will decrease total energy demand	Policies to overcome barriers and path-dependencies; Phasing out existing carbon-emitting capital stock and fossil fuel subsidies; A greater number of aggressive targets for energy efficiency improvements and renewables required now; Feed-in tariffs	Immediate action is necessary	Behavioural changes, such as managing energy use better, can provide the most rapid energy and emission reductions	Transition of global energy system should be accelerated by scaling up success stories and sharing strategies across national borders	-	Yes, both private and public R&D	Yes, carbon price should increase annually	Potential of renewable energy sources significantly underestimated in most studies (see also AEE, 2009); Conversion of electricity and transport sectors can turn the 'supply follows demand' principle onto its head, as smart grid and sufficient energy storage can make demand follow supply[1]
McKinsey (2009) To 2030 Five scenarios of global emission pathways, with three of them showing increase in emissions, with implications for more than a 2 °C warming by the end of the century	Potential to reduce global emissions by 35% from 1990 levels by 2030	The study intentionally avoids a discussion on best policies, but the following areas should be addressed: overcoming barriers to energy efficiency improvements, long-term incentives for low carbon technologies, linking GHG abatement in forestry and agriculture to overall development agenda; encouraging behavioural changes also important	All sectors and major world regions need to start acting now; Action delayed until 2020 would make it virtually impossible to stay below 2-degree warming	Opportunities for behavioural changes: reducing travel, shifting from road transport to rail, reducing heating/cooling, reducing appliance use and meat consumption; Organisational problems in firms related to energy efficiency improvements mentioned	-	Acknowledged, but not modelled in	Most likely yes, but not discussed in detail	Yes, the models in the study include a price of €60 per tonne	Includes GHG abatement cost curves for 2015 and 2030.

[1] For example, in the US, the power output capacity of all vehicle engines together is about 10 times more than the US electricity grid output capacity (Worldwatch Institute and the Fletcher School, 2009).

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World Bank (2007) To 2030 Global economic scenarios, where climate change is an externality, potentially threatening growth	No specific level is discussed, but the Stern Review target of 60-80 percent by 2050 (from 1990 levels) is mentioned	Policy examples: Removing barriers to behavioural change - e.g. transaction costs, organizational inertia, and a lack of reliable information - through regulation (for example, minimum standards for buildings and appliances), labeling, and sharing best practices, and financing the upfront costs of efficiency improvements (which has large potential in transport, new buildings and industry); International framework for emissions trading to encourage energy efficiency, technological cooperation to ensure more rapid adoption, action to reduce deforestation, and assistance to poor developing countries to promote adaptation	Immediate action, including an emissions reduction target is necessary, but no immediate target is discussed, only the Kyoto protocol	Organisational inertia and behavioural change mentioned	-	-	Additional R&D should be encouraged, details not discussed	Yes, no specific price discussed; emitting other GHGs should potentially also be priced	Renewables estimated to grow, but not much in terms of proportion of total energy consumption; Switching from coal to natural gas
International Energy Agency (2010d) To 2035 *Current policies scenario*: policies of mid-2010 continuing without change, CO2e concentration peaking at more than 1000 ppm *New policies scenario*: cautious implementation of Copenhagen pledges and the removal of fossil fuel subsidies; CO2e concentration stabilizing at 650 ppm, likely resulting in over 3.5°C temperature increase 450 scenario included here: limiting long-term atmospheric CO_2e concentration to 450 ppm	Long-term stabilisation at 450 ppm CO2e with an overshoot at 520 ppm around 2040; Total GHGs 40% lower than 1990 levels by 2050, declining from 2020	Policy examples: Encouraging end-use efficiency; Removing subsidies on energy consumption; International sectoral emission reduction agreements for the iron and steel, and the cement industries; International agreements on fuel-economy standards for passenger light-duty vehicles, aviation and shipping; Efficiency standards for buildings and labelling of appliances; Extending public support for R&D and deployment of renewable energy sources; Extending the lifetime of nuclear power plants; Specific to EU: Directive on the geological storage of carbon dioxide; Extended mission targets for passenger light-duty vehicles and light commercial vehicles by 2020; Enhanced support to alternative fuels; National EV targets; Aviation and international maritime shipping in ETS from 2013; Directive on energy efficiency including the development of inverters for electric motors, high-efficiency cogeneration, mechanical vapour compression and emergence of significant innovations in industrial processes; Nearly zero-energy buildings standards mandatory for new construction as of 2020 and zero-carbon footprint for all new buildings from 2018	EU target assumed 30% by 2020; Implementation by 2020 of the Copenhagen (high-end of the range) emission reduction pledges; OECD+ with reduction targets from 2013; After 2020 targets extended to other major economies (Brazil, China, Russia, South Africa and the countries of the Middle East);	Behaviour changes would significantly facilitate the implementation of the 450-scenario; Removal of fossil fuel subsidies would be likely to change behaviour, i.e. reduce demand for energy in the long run	-	Discussed; Suggested solution in the context of fuel efficiency gains is to keep end-user prices the same (as before efficiency gains) by raising VAT or other taxes on transport fuels	Yes, both public and private R&D funding for more advanced technologies	Yes, $45 per tonne by 2020 and $120 in 2035 in OECD+, and from near zero in 2020 to $90 per tonne by 2035 in other major economies	A profound transformation of the global energy sector is required, but today's technologies are enough; Efficiency improvements can offer 71% of necessary emission reductions by 2020 and 48% by 2035; CCS can offer 2% of emission reductions by 2020 and 19% by 2035; Nuclear power in total electricity generation 50% more in 2035 than currently; Share of renewable in electricity generation 250% more than today by 2035
Victor (2008) To 2035 Model of Canadian economy with low/no GDP growth	Should be at least 60% by 2050	Examples: Policies required in investment (using taxes to discourage excessive investment in new capital), productivity (redirecting increases in productivity to something other than throughput, e.g. leisure time), and technology (comprehensive technology assessment for new technologies)	Immediate action necessary; Required rate of improvement in carbon intensity (through technological improvements) is very high, GDP and population growth need control as well at the global level	Behavioural issues discussed, e.g. energy efficiency improvements have to be coupled with behavioural changes	Discussed to some extent	Rebound effect can potentially eliminate efficiency gains	-	Yes, a high price preferred (the scenario uses $200 per tonne)	Technological improvements should not be relied upon too much; General welfare and environmental - especially climate change - objectives can be met without positive GDP growth being a necessary goal for industrial countries
World Business Council for Sustainable Development (2010)	Energy related CO2 emissions decline 50% from 2005 levels by 2050 (GHGs peaking	Examples of policies for 2020: Regular building audits by governments to measure performance, identify improvement opportunities,	Immediate action necessary, no specific immediate targets	New partnerships between different actors and areas of expertise – public,	Some discussion	Not mentioned specifically, but implicitly there in the discussion on behaviour	Yes, both public and private	Yes	Shift in business thinking: climate change and resource constraints are economic (not environmental) problems -> leads to

Scenario (Years covered; main focus)	Eventual percentage decline in GHGs	Policies for 2020, 2030 or 2050	Immediate reduction targets	Behavioural or organisational issues	Problem of transitions	Rebound problem	Additional R&D for low carbon technologies	Price on carbon	Technology-economy conclusions / Economic indicators
To 2050 Sustainable growth scenario	around 2020); material and energy efficiency improvements by factor 4-10	and establish implementation priorities in most developed countries; Mandatory standards for buildings' thermal integrity and heating systems across the OECD; Mandatory recycling and optimized packaging in OECD countries; <u>Examples of policies for 2030</u>: Global standards for buildings' thermal integrity and heating systems; Global mandatory energy labelling of all appliances; <u>Other examples of policy aims</u>: lowering the costs of renewable electricity production and improving the efficiency of other forms of production; establishing continental-scale electricity grids		private, civil and academic sector individuals and organizations needed to tackle the challenges (business structure and culture may need re-engineering for this); Social innovation important, e.g. for new business models, new customer behaviour and action, and new ways of interacting between providers and users; Behaviour changes discussed in detail		change			a 'green race'; GDP should be supplemented with other measures linked to negative externalities; Halving CO2 emissions achieved by shifting to low-carbon energy systems and mobility, and by strongly improved demand-side energy efficiency; Existing knowledge and technologies are enough
PriceWaterhouse Coopers (2010) To 2050 Roadmap for 100% renewable electricity production for Europe and North Africa; Argues for a regional solution to climate change; Includes a detailed map of action for policy, markets, investments and infrastructure.	90% reduction in GHGs by 2050; 50% of electricity from renewables by 2030, and 100% by 2050	Roadmap includes specific milestones for short-term (2010, 2012, 2015), medium-term (2020, 2030) and long-term (2040, 2050) for the necessary transformation in government policy, market structure, investment and infrastructure to achieve the 2050 goal; Rewriting of energy policy and legislation is necessary to change the rules and incentives; For example, guidance for the implementation of Article 8 of the Renewables Directive dealing with imports of electricity, and the development of a new directive on grid regulation mandating long term EU-level planning of grid infrastructure (enabling more ambitious short-term national targets for renewable energy)	EU targets for 2030-2050 in terms of climate and energy set in 2015	Essential lifestyle changes are not required in this plan; Organisational challenges include having adequate human resource capacity, which can be helped by coordination between countries and regions	Discussed in the context of the roadmap, plus additional areas of further research	-	Yes, substantial investment, both public and private	Yes, the price should be strong and stable	System based on the SuperSmart Grid idea; Diverse range of energy supply sources necessary; Conversion of transport and electricity sectors; Large scale investment can make wind power and CSP cheaper than fossil fuels in 10 years; Most suitable sites for most suitable technologies and a unified electricity market (EU and NA) should be production principles
Netherlands Environmental Assessment Agency and Stockholm Resilience Centre (2009) To 2050 Scenario works back from 2050 what needs to be done in the next 5-10 years to meet the goals of population growth, climate change mitigation and specifically, a low-carbon energy system for the EU	At least 80% reduction in CO2 emissions by 2050, compared to 1990 levels (50% by 2030)	Confidence in long-term policy targets built by living up to short-term targets and by institutionalising long-term agreements and obligations; For example, an EU climate law or obligation for Member States to develop such a climate law could establish reliable long-term targets; Policy coherence between issues and sectors is important (e.g. in transport and energy); Strategies should prevent lock-in to interim solutions and look at the bigger picture, diversity in approaches and solutions, and need for balanced consumption; <u>Specific policy examples</u>: Bio-energy should only be used when no low-carbon alternatives currently exist and where it pays most (e.g. road freight transport or aviation); Currently available no-regret technologies, such as heat pumps, solar PV and wind power should be stimulated in a coordinated way; Emission standards need to be set for new power plants, a clear target for phasing out fossil power plants without CCS (e.g. no new plants without CCS from 2025), and long-term tar-	Immediate action is necessary; A 30% GHG emission reduction in the EU needs to be achieved by 2020 (for a reasonable chance for the 2-degree goal)	Behavioural changes required, e.g. in air travel (more high-speed train instead of air travel), energy use, general consumption (through awareness raising and e.g. a tax on fuel carbon content)	Discussed; Solutions include substantial R&D investment to get transition process started, linking increased use of natural gas to CCS to prevent lock-in, reliable long-term policy targets	-	Yes, substantial funding and international cooperation	Yes	Continental scale power grid necessary; Emissions from transport (with predicted growth) have to be cut by a factor of 12; Deployment of low-carbon technologies should be accelerated after 2020

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		gets for decreasing emissions of GHGs							
Lazarus and Kartha (2009) To 2050 Scenarios examine metrics for technology development, and the impact of shadow carbon pricing and much increased R&D in known energy technologies on global energy-related carbon emissions	No specific emission reduction target, but 2-degree limit mentioned as a general policy goal	Necessary objectives for low carbon technology development include (in addition to R&D): building technological capacity, establishing new institutions, mobilizing political constituencies, creating new classes of assets, opening financing channels, and eliminating subsidies and other policy biases in favour of incumbent technologies[2]	Action required now, no specific short-term targets	Business and individual behaviour change necessary	-	-	Yes; However, direct conclusion from the scenarios: increased R&D on existing technologies may deliver only limited results in terms of emissions reductions (as compared to carbon pricing); however, this modelling has many uncertainties, and most importantly, can only really focus on existing technologies and incremental change	Yes; Direct conclusion from the scenarios: Carbon pricing may be more efficient in reducing emissions than increased R&D (see R&D column); the scenarios explore different levels of carbon price	Generally, exploring metrics for effort and outcome in technology development, deployment and transfer, as well as direct environmental policy is useful
International Energy Agency (2010b) To 2050 Looks at the potential of one renewable energy technology – concentrating solar power (CSP)	By 2030, CSP can provide 6% of European electricity, and by 2050 15%, mostly from imports	The CSP roadmap can be implemented with the help of European initiatives such as the Mediterranean Solar Plan and the DESERTEC Industry Initiative; Policy action examples: Establishing an equitable environment for CSP development through feed-in tariffs or binding renewable energy portfolio standards, encouraging state-controlled utilities to bid for CSP capacities, streamline permit procedures for CSP plants and access lines, offering suitable land and access to grid or water resources, and waiving land property and other taxes, as additional means for quick-start deployment, developing incentive schemes for solar process heat and fuels, not just electricity, progressively eliminating subsidies to fossil fuels	Immediate action to meet the roadmap targets	-	-	-	Yes, both public and private	Yes	CSP is a proven technology, a firm but flexible source of electricity, and can help with intermittent sources; CSP can be competitive for base loads by 2030 in the sunniest countries, (mostly not in Europe though); The abundant sunlight in the Middle East and North Africa will lower costs, compensating for the additional expected transmission costs and electricity losses for importing from ME or NA
International Energy Agency (2010c) To 2050 Looks at the potential of one renewable energy technology – solar photovoltaic energy (PV)	By 2050, PV can provide 11% of European electricity according to this scenario, but industry estimates go as high as 12% already by 2020; This roadmap's Annual emissions reductions of more than 2 Gt CO2 could be achieved by 2050	Achieving 12% of EU electricity from PV by 2020 would require quick adoption of smart grid technologies and power storage; Policy areas: Creating a policy framework for market deployment now and in the next decade, including incentive schemes to accelerate market competitiveness, improving financing models and training and education to foster market facilitation and transformation	Immediate action to meet the roadmap targets	-	-	-	Yes, both public and private	No discussed	PV can be grid competitive by 2020 in many European regions
International Energy Agency (2010a) To 2050 *Bluemap scenario* to achieve a 50% reduction in CO2 emissions uses a techno-economic approach that assesses costs and benefits, and examines least-cost pathways for meeting	In the BLUE Map scenario, CO2 emissions in 2050 are reduced to 14 Gt, around half the level emitted in 2005. This means emissions are 43 Gt lower in 2050 than the 57 Gt CO2 projected in the Baseline scenario. Achieving these CO2 emissions reductions will require the development and deployment of a wide range of	The following policies are proposed without indication of their timing: - Regulatory or control mechanisms such as energy building codes or minimum energy performance standards for appliances. - Fiscal or tax policies - Promotion and market transformation programmes - Financial remediation measures in the form of special financing or lines of credit for energy-efficient technology investments.	None are being proposed	The report refers to the theory of planned behaviour as an alternative model than the model of techno-economic assessment which is used	It is mentioned that policy change requires time and that many technologies have long development times	Rebound effect is discussed in relation to fuel economy improvements in transport where it is stated that a 20% rebound effect would trigger a 6% to 7% increase in driving, with a similar increase in fuel use and CO2 emissions, all else being equal.	A two to five fold increase in public expenditure for low-carbon energy RD&D is proposed. The shortfall in annual investment needed to achieve Blue map objectives is estimated at between 40 and 90 billion USD. The greatest downfall is for advanced vehicles (21-43 bn USD), CCS (8-17 bn USD), smart grids (5-11 bn USD) and energy efficiency in industry (4 – 9 bn USD)	No price is being proposed but the report proposes the use of carbon prices (while stating that they are necessary but not sufficient)	Doubling of energy efficiency rate from 0.7 to 1.5 per year (which will produce the largest share of emission reduction: 38%) Completion of 100 large scale CCS projects by 2010 and 3400 projects by 2050 (producing emission savings of 19%) Half of total electricity generation from renewable energy sources (compared to 18% today), which will produce 17% of the total emission reduction. The most

[2] Reform of fossil fuel subsidies could reduce global CO_2 emissions by up top 8% and by up to 20% in selected countries where subsidies for fossil fuels are more pronounced (Lazarus and Kartha, 2009, p. 41). Also IEA (2010d) emphasizes the emission savings that can be made by removing fossil fuel subsidies.

Scenario (Years covered; main focus)	**Eventual percentage decline in GHGs**	**Policies for 2020, 2030 or 2050**	**Immediate reduction targets**	**Behavioural or organisational issues**	**Problem of transitions**	**Rebound problem**	**Additional R&D for low carbon technologies**	**Price on carbon**	**Technology-economy conclusions / Economic indicators**
energy policy goals whilst proposing measures to overcome technical and policy barriers. The report also contains *technology roadmaps* for CCS, cement, electric and hybrid vehicles, CSP, solar PV and wind energy and *country reports* for the USA, China and India (plus a report for OECD Europe)	energy-efficient and low-carbon technologies across every sector of the economy	- Commercial development and industry support mechanisms In addition, the report proposes the following policy design principles: -Policies should be transparent, stable and predictable in the long term to minimize investor uncertainty -Incentives and mandates should reflect the maturity of different technologies. Levels of support should decrease over time as the technologies become competitive. -Policies should encourage the development of both generation and transmission technologies. -Technology push and market pull incentives should be part of a coherent, strategic framework and supported by measures that address administrative or other barriers faced by technologies. -Governments should encourage energy output rather than the installation of technology. -Policies should be easy to implement and enforce, with appropriate penalties for non-compliance. The following enabling actions are proposed: fostering industry leadership; developing a skilled low-carbon energy workforce; expanding public outreach and engagement; strengthening international collaboration				It is also said that even in those instances where rebound has occurred, efficiency gains have been substantial			important renewable energy sources are onshore wind and solar PV, with an annual increase of 48 GW and 46 GW, respectively. 30 new nuclear plants of 1000MW to be built every year from 2010 to 2050 Rapid diffusion of plug-in hybrid electric vehicles and full electric vehicles from 2015. Quarter from transport fuel from sustainable biofuels by 2050.
European Climate Foundation (2010) To 2050 Baseline and three pathways : 80% RES; 10% CCS; 20% nuclear 60% RES; 20% CCS; 20% nuclear 40% RES; 30% CCS; 30% nuclear	80% below 1990 level by 2050 (95% reduction in power sector emissions)	Action to convert the non-binding 2020 efficiency goal into a binding requirement; update the EU ETS to meet current 2050 greenhouse gas reduction goals, alongside additional, complementary measures that reinforce incentives to invest in low/zero carbon resources, rule out investment in long-lived high-carbon generation and overcome market barriers to energy efficiency measures; a new 'Climate and Resources' framework to create the policy mix that will efficiently deliver the climate targets and address resource constraints across sectors beyond 2020 and out to 2050; review of EU budget allocation to ensure appropriate funding is allocated to investments in renewables, CCS, energy efficiency and network infrastructure; expansion of the ACER/ENTSO-E mandates to develop a strategic interconnection plan; aggressive targets and strategies for the deployment of energy efficiency measures that	Immediate investment in low-carbon energy technologies; Aggressive energy efficiency policies, as energy efficiency is the lowest cost and most immediately assessible way to reduce carbon emissions, reducing the need to which abatement must be delivered through other means and reducing energy bills for consumers	An integrated energy market which supports efficient cross border trading (something which requires changes in the mandate of network regulators). One-stop-shop delivery of energy efficiency improvements by a qualified and capable entity under performance contract with the government. Demand side management through smart grids	Attention to the need to phase out high-carbon technologies. ETS should be accompanied by measures which rule out investment in long-lived high-carbon generation – both in new plant and in the life-extension of existing plant	Attention to extra growth in electricity because of electrification of transport and heating sector, but no estimation of rebound effects from money saved	The pathways do not rely on technology breakthroughs, but R&D support for, e.g., enhanced geothermal systems, largescale electrochemical storage and new, potential breakthrough technologies will enable the transition faster and at lower cost. No concrete proposal for extra R&D funding is being given	Average CO2 price of 20-30 € per tCO2e over years	The new installation and replacement of close to 100,000 wind turbines (of which half could be at sea), equaling 2,000 to 4,000 new wind turbines per year. On average, the installation of about 5,000 square km of solar panels over 40 years, equaling about 0.1% of the area of the EU,A factor-three increase of inter-regional transmission capacity. Approximately 190 to 270 GW of backup generation capacity (representing 10 to 15% of total 2050 generation capacity). The deployment of potentially up to 200 million electric and fuel cell vehicles and potentially around 100 million heat pumps for buildings or city districts across Europe. The transition requires about € 7 trillion of investment over the next forty years; the new technology investments could create between 300,000 and 500,000 jobs.

Scenario (Years covered; main focus)	**Eventual percentage decline in GHGs**	**Policies for 2020, 2030 or 2050**	**Immediate reduction targets**	**Behavioural or organisational issues**	**Problem of transitions**	**Rebound problem**	**Additional R&D for low carbon technologies**	**Price on carbon**	**Technology-economy conclusions / Economic indicators**
		will double to triple the current rate of overall energy efficiency improvement; deployment targets beyond 2020 for key renewables generation technologies such as off-shore wind, solar PV; consider parallel deployment strategies for CCS, especially in heavy industry; <u>review of wholesale market arrangements</u> to ensure that incentives promote investments in energy efficiency and other demand-side resources; <u>system balancing and t cross border trading</u>; timetable for implementing fully smart power networks; review spatial and environmental planning laws; <u>ensure proper sources of funding</u> for the new low carbon infrastructure							About 250,000 jobs could be at stake in the fossil fuel industry. Potentially € 25 billion exports annually. The cost of decarbonised electricity is € 100 per household
Shell (2010) *To 2050* *Scramble scenario* in which national governments are principal actors who are more concerned with energy security for economic growth than with climate policy, leading to a flight into coal and non-conventional oils. *Blueprint scenario* with initiatives first taking root at the local level, gradual expansion of policies and measures Both scenarios are based on management's current expectations, they are not target-based	GHG consequences of the scenarios are not given but GHG is likely to increase significantly given the projected increases of primary energy with 110% and 84% with fossil fuels accounting for 58% and 63% of total primary energy. In the scramble scenario CO2 emissions will continue to rise until 2050	In one scenario energy security is the main policy concern for reasons of making sure that supply meets growing demand for energy. In the other scenario, policies for climate mitigation develop in a bottom-up manner, with an important role for cities. The US is expected to opt for corporate average fuel economy standards for cars and Europe for carbon trading. There will be global CO2 emission trading systems by 2020 involving the US and China	In none of the scenarios are nations expected to set ambitious reduction targets	New coalitions of interests for issues of energy supply, environmental protection and associated entrepreneurial opportunities	The scenarios are sophisticated stories of the future, based on geopolitical considerations, with policies being driven by interests. A strong element is the attention given to bottom-up developments (of cities) and geopolitical interests	Not discussed, the focus is on energy supply to meet demand rather than GHG emission reduction	Expected to grow.	This will come slowly, and will come about through national policies rather than international agreements	It is said that we are heading towards a world of electrons rather than molecules but electrons will be produced to a large extent by fossil fuels which will account for 58% and 63% and primary demand by 2050. time paths are being given for low-carbon fuels and technologies. By 2030 20% of coal and gas fired power generation equipped with CCS in the most green scenario. Around 2030 50% of new sales are electric or hydrogen in the green scenario. In 2050 biofuels will account for 30% of liquid fuels in both scenarios. Nuclear will experience ups and downs.