Per Ivar Karstad

Norwegian value creation beyond oil and gas

Strategic opportunities in sustainable Norwegian energy production to secure European energy supplies

Thesis for the degree of Philosophiae Doctor

Trondheim, November 2009

Norwegian University of Science and Technology
Faculty of Engineering Science and Technology
Department of Geology and Mineral Resources Engineering

NTNU
Norwegian University of Science and Technology

NTNU
Norwegian University of Science and Technology

Thesis for the degree of Philosophiae Doctor

Faculty of Engineering Science and Technology
Department of Geology and Mineral Resources Engineering

ISBN 978-82-471-1821-4 (printed ver.)
ISBN 978-82-471-1823-8 (electronic ver.)
ISSN 1503-8181

Doctoral theses at NTNU, 2009:210

Printed by NTNU-trykk

Table of Contents

List of figures

List of tables

Preface

The work presented in this PhD thesis was carried out at the Department of Geology and Mineral Resources Engineering at NTNU from January 2006 until December 2008. The project was funded by Statoil ASA and was carried out in close cooperation with the Strategic University Program “Green Innovation”.

This work has been an enjoyable and challenging mental process. As an employee of Statoil ASA in the Oil and Gas division, I started out with the approach that climate policies probably would harm the market for oil and gas companies. After reading some literature related to climate change, I realised that it is the other way around. We have an obligation to make sure that the energy system becomes sustainable.

Humans are very short sighted, and prioritise economic growth and increased welfare at the expense of the environment. The total energy use is strongly coupled to the size of the economy, and the type of energy use is coupled to the type of capital goods that we have invested in. This takes time and resources to change. A strong disruptive change might be needed to shift the energy system into a different and sustainable path. This change could be a “peak oil” situation, accelerating climate costs, political and economical instability or even war.

I think we have to change the energy system. I think we will remain short sighted, continue to optimise welfare and hope for the best for the future generations. Change towards sustainability has to be done within this context.

Can “peak oil”, climate policies and technological learning create business opportunities for sustainable energy production, or is there a need for a stronger force to move down the learning curve? Can Norway use this opportunity to create a competitive position within sustainable energy production capable of replacing the value creation in the Norwegian oil and gas industry? Hopefully, this thesis would serve as a strategic basis for evaluation of policy options to increase Norwegian welfare.

Executive summary

The best way to predict the future is to invent it.
(Kay 1994; quoted in May 1996 p 157)

Norwegian oil production has passed the peak and is currently declining. It is likely that Norway will be a net importer of oil within two decades. Norwegian gas production is expected to remain high in the next two decades before it will start to decline. To maintain the Norwegian welfare beyond the oil and gas era, alternative businesses are required to maintain Norwegian value creation. This thesis investigates the future contribution of sustainable energy production to the future Norwegian value creation. The major drivers for change in the future energy markets are expected to be energy security and climate policies. This thesis investigates the following question:

> How can Norway develop an industry based on sustainable energy production capable of replacing the declining value creation from the Norwegian oil and gas industry?

Scenario analysis and system dynamic modelling are used as the basis for a strategic analysis and estimation of future Norwegian value creation in offshore wind production and carbon capture and storage (CCS).

This thesis finds that the global energy market will be increasingly dependent on limited oil and gas supplies from a limited number of geopolitical unstable locations with high investment risks. It is likely that it will be increasingly more difficult to maintain a high production level of fossil fuels due to resource constraints and geopolitical instability, leading to increased insecurity in energy supplies.

There is a common view that climate change will lead to severe changes in the long run and have major implications for human society. Due to the long time between cause and effect, climate changes will occur rather slowly. The industrialised world can adapt to most of these changes while climate change will be more damaging in the developing world (Stern 2007, p xix). Due to the potential severe implications of climate change the precautionary principle developed by the UN should apply to global

climate policies (UN 1992). This work estimates the accumulated European cost of climate damages due to CO_2 emissions to $129 per metric ton by the end of this century in the modelled reference case. These costs are expected to increase exponentially into the future due to the irreversible nature of climate changes.

This thesis finds that reproduction of energy-related CO_2 emission scenarios by the Intergovernmental Panel on Climate Change (IPCC) requires fossil fuel resources three times higher than the level currently estimated by the International Energy Agency (IEA) (IPCC 2007c, p 187; IEA 2008b, p 218). This study finds that future CO_2 emissions from estimated fossil-fuel resources seem insufficient to cause a catastrophic climate development. However, coal resources are very uncertain, and to ensure stabilisation of atmospheric CO_2 concentration it is necessary to implement global policies that lead to extended use of renewable energy and CCS at coal power plants.

It is found that climate change may reduce welfare and associated energy demand. Limited fossil energy resources may temporarily limit the economic growth until high energy prices lead to energy efficiency gains and renewable energy production capacity to fuel further growth. This economic setback may be eliminated by proper energy policies to promote renewable energy production.

This work concludes that CCS is unlikely to play a significant role in the future value creation in Norway, while offshore wind has the potential of becoming a major Norwegian industry. A more active policy towards climate change in Norway, aiming to develop renewable energy production, can change the path of the energy system in Norway and Europe towards a renewable path at acceptable costs. This will be beneficial for Norway and for Europe in terms of value creation, energy security and climate mitigation.

The analysis in this thesis shows that future value creation from offshore wind production on the Norwegian continental shelf, delivering electricity to the European market, is comparable to the value creation from the current Norwegian oil and gas industry. Development of an offshore wind industry in Norway can increase the accumulated Norwegian value creation by more than 10 %, or more than $ 2500 billion, by the year 2100 provided that Norway acts early to create competitive advantages in respect of European industries. Sensitivity analysis using the simulation model developed in this work (CE2-model) indicates that severe climate change may reduce the potential value of Norwegian offshore wind resources. It is therefore in Norway's interest to achieve strong international cooperation to reduce global CO_2 emissions.

A portfolio standard is a regulatory measure to increase the fraction of renewable energy in the total energy mix. A policy based on portfolio standards for CO_2 emissions combined with a carbon taxation that is reinvested in renewable energy production and CCS seems to be the most efficient policy in terms of accelerating renewable energy production and carbon capture and storage to reduce global CO_2 emissions significantly (Gerlagh and Zwaan 2006). The modelling in this study finds that a global carbon tax of $90/ton would contribute to a 50 % reduction in global energy-related CO_2 emissions without harming the world economy. This would limit the increase in average temperature on earth to 3 ^{o}C relative to pre-industrial temperature.

The analysis in this work lead to the conclusion that developing a leading industry based on sustainable energy production in Norway will require stable policies over several decades and instruments such as:

- Include the environmental costs of CO_2 emissions in the cost of energy and products through a carbon tax of $90/ton (Internalise Externalities).
- Recycle carbon tax back to renewable energy investments.
- Establish public procurement programmes where governments require a high degree of renewable energy in public purchases.
- Increase public R&D on renewable energy.

To achieve sustainable development, economists need to think differently on how to define economic development and to a larger extent include the value of natural resources in the measurement of economic development. Governments should focus more on increasing the long-term value of the national resource base of natural capital, human capital and manufactured capital, rather than the present way of thinking, where short- term outputs from these resources are optimised. Second, governments must internalise externalities in energy prices without discounting future generations. A change towards a sustainable energy system is urgent. The energy system becomes more locked-in to fossil fuel as more investments are directed towards these energy types. A shift towards sustainable energy production will require greater efforts the longer decisions to change are deferred.

This work describes how Norway can unlock the path to a sustainable energy future and contribute to a change in the global energy supply system toward sustainability.

Acknowledgements

First of all I would like to thank my supervisors, Kai Nielsen, Knut Erik Solem and Kaare Gether, for their encouragement, their helpful opinions, discussions and patience throughout my PhD work. This has been a challenging task where the directions have changed as we have learned more.

I also have to thank Dag Vareide, Rolf Utseth and Birgitte Schilling at StatoilHydro ASA for their financial and morale backing when this research project was initiated. My manager Bjørn Berger has been extremely helpful in protecting me against the corporate system, to give me time and space to develop this work. Without their support, none of this could have been done.

I am grateful for all the enjoyable discussions I have had with Harald Gether and for his contribution to realise the project at NTNU. Without his contribution and encouragement this could not be realised. A special thank to you!!

During my research visit to the University of California at Berkeley from August 2007 to December 2007 I had the pleasure of meeting and gaining experience from a number of people. In particular I would like to mention Alexander Farrell, who unfortunately passed away last spring, who helped me understand the energy challenge, while Inez Fung helped me to understand the climate challenge. A special thank to Trond Pettersen for organising my research visit at UC Berkeley.

I have had the privilege of discussing my work with a group of people consisting of Christine Neset from corporate strategy in StatoilHydro, Susan Ruth from CERA and Jørgen Randers from the Norwegian School of Business. Their input to this work has been very valuable and I appreciate their contribution very much.

Steinar Moen at Powersim AS has played a crucial role in improving my modelling knowledge, for quality control of the model and for practical advice regarding modelling functionality.

A special thank to Tore Undeland who, on short notice, stepped in to help me with the final touch of the thesis. His contribution is very much appreciated.

I owe my sincere thanks to my fantastic family for their support and backing during this work. Without my wife Sissel's patience and sustained support throughout this work it would have been impossible to realise. Thanks to my children, Eline, Benjamin and Isak Sebastian, for the joy they bring. Their future is the main motivation for this work.

1 Introduction and scope

There is currently a strong focus on climate change globally. There is also a growing concern about energy security in many energy-importing nations. This contributes to increased demand for clean and secure energy supplies. The purpose of this thesis is to investigate the potential value creation of a transition from oil and gas production towards environmentally sustainable energy production in Norway. The potential for value creation of two business opportunities, Offshore Wind Power and Carbon Capture and Storage, have been estimated using scenario analysis, system dynamic modelling and net present value calculations (NPV).

As illustrated by the Norwegian Petroleum Directorate (NPD) in figure 1 below, Norwegian petroleum production has peaked, and is now approaching a decline phase (NPD 2005), which eventually will create a need for new business development and value creation in Norway to maintain the current welfare level.

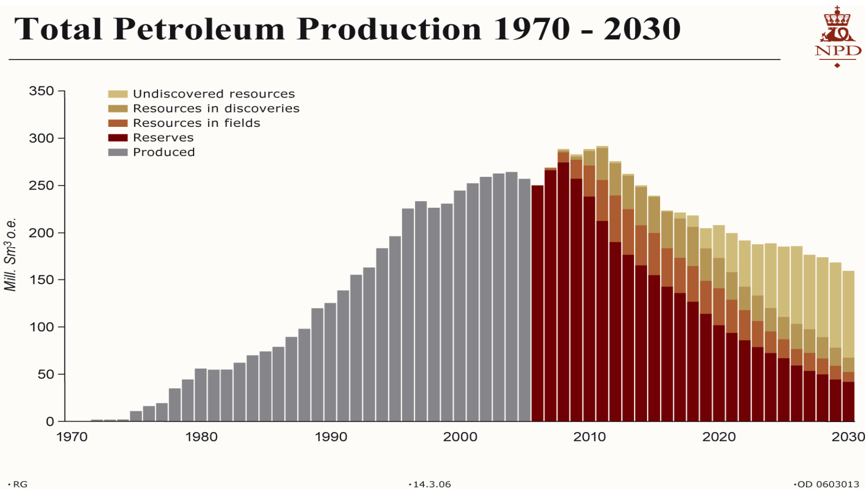


Figure 1: Total Petroleum Production on the Norwegian Continental Shelf 1970–2030.

Norway is a significant oil and gas producing nation. The decisions of the European nations, Norway's main market, with respect to energy and climate policies will have major impact on the value of the nation's oil and gas reserves. The transition towards a sustainable energy system in Norway and in Europe is an opportunity for industrial development to secure welfare for future generations in Norway. This opportunity can potentially be developed into a major export industry aiming to supply the European market, given the right incentives and support from the Norwegian government. A new industry based on sustainable energy production can contribute to close the gap between future value creation and the future cost of public services and welfare as predicted by Statistics Norway and illustrated in figure 2 below (Sand, Schiefloe et al. 2005, p 178). New industrial development in Norway is required to close the estimated value creation gap of $40 billion per year by 2030.

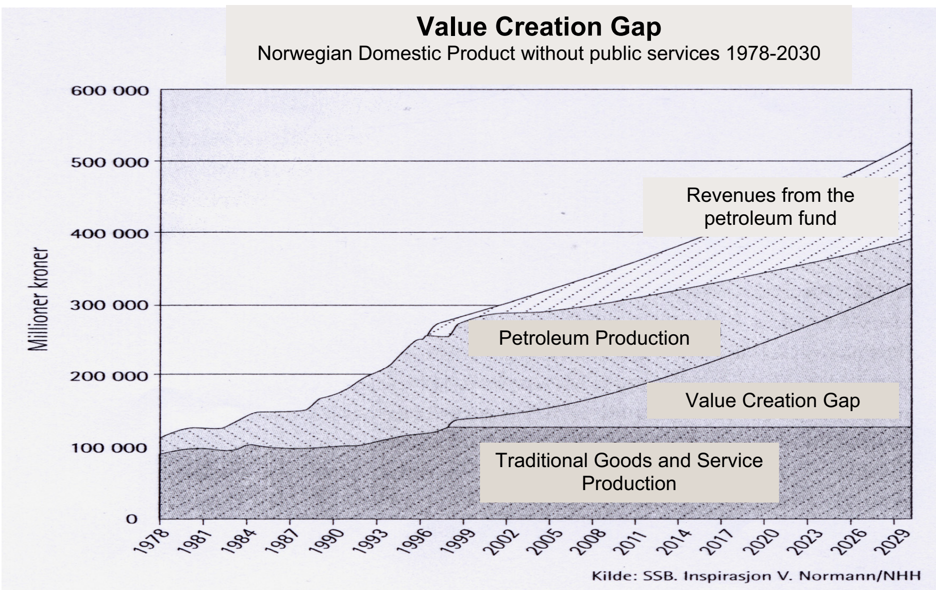


Figure 2: Norwegian Value Creation Gap (Sand, Schiefloe et al. 2005, p 178)

At the same time as the petroleum revenues decrease in Norway, the costs of the welfare system in Norway will continue to increase as the share of the elderly population increase, leaving an increasing economic burden on the working population (Stortingsmelding 2009, p 63, 140). Norway has to develop new industries capable of replacing the petroleum revenues to secure the capacity to maintain the public welfare system in Norway beyond the petroleum era.

The task is highly interdisciplinary and complex. The value of environmentally sustainable energy production is influenced by two main elements; contribution of energy supplies to economic development and reduced cost of climate change.

Understanding the risk and uncertainty of energy supply interruptions and climate change are important in order to estimate the potential threat to the future welfare. This work investigates how Norway can achieve the required technological innovations for development of sustainable energy production. This thesis investigates the following question:

> How can Norway develop an industry based on sustainable energy production capable of replacing the declining value creation from the Norwegian oil and gas industry?

This thesis investigates the impact of climate policies and energy security on European energy demand, and the impact of innovation policies in Norway and Europe on zero emission energy supplies to the energy market. This thesis focuses on the European energy market because the growth in the Norwegian energy market seems insufficient as the driver of a major industrial development. The main focus in this work has therefore been to investigate the future value of electricity exports from Norwegian sustainable energy production to the European market. Offshore wind and gas power with CCS has been the main focus in this thesis due to the limited expansion potential for hydro power, onshore wind and solar power in Norway.

The energy future can be created but will require visions to guide the path to the future. The society will only realise a sustainable energy future if it decide to get there (Hamel and Prahalad 1994). This work may contribute to discovery of a path to a sustainable future.

This thesis aims to identify options to close the future Norwegian value creation gap through industrial development within sustainable energy production to secure European energy supplies. The work presented here leads to the conclusion that Norway has at least one option to close the value creation gap. It is through a focused effort to develop an offshore wind industry in Norway.

2 Theoretical background

The Earthscan report, “Limits to Growth – the 30 year update” (2005) claims that the global system is currently in an unsustainable situation, and that there are limits to growth on the planet – limits on resources, food, environment, and to the population the Earth can support over time (Meadows, Randers et al. 2005, p 234). Meadows et al. (2005) concluded that the people of the world have to act soon to establish a sustainable world. Without actions to create sustainability, the global population will face enormous challenges in providing sufficient goods, energy and food to a growing population. Future generations may experience recession, hunger, conflicts, and reduced living standards (Meadows, Randers et al. 2005, p 176-179).

The global population is expected to increase by 30 % in the next 25 years, of which 80–90 % of the growth is expected to be in developing countries (IEA 2004, p 43-46). To establish a sustainable global development, with growth in population and living standards, it will be necessary to develop sustainable energy production and improved energy efficiency.

The main question from the previous chapter can be divided into the following sub questions:

- What is sustainable energy production?
- How large are the different energy production potentials?
- What is the climate impact of energy production?
- How will climate policies develop?
- How can the Norwegian value creation and welfare be sustained?

This chapter will set the scene by investigating main elements that influence the development and value creation in future energy markets as described in the questions above. Energy demand depends mainly on economic growth which might be slowed down by climate damages, while energy supplies depend on energy security and energy price. The background in this chapter provides the basis for modelling and analysis of the energy and climate challenge as illustrated in figure 3 below.

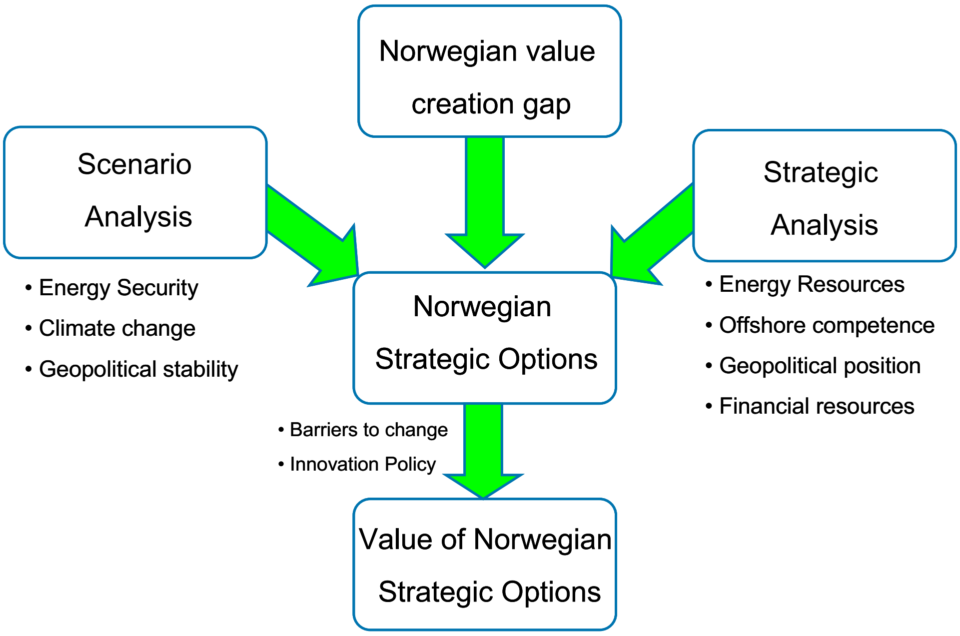


Figure 3: Work flow in the thesis

The energy markets in the last years have been characterised by a substantial increase in global energy demand, especially in China and India, caused by the strong economic growth in these countries. At the same time it is observed that the capacity to deliver fossil energy may be limited due to limited production capacity and lack of infrastructure development, such as pipelines, refining and terminal capacities (Ruth 2005). Nations are concerned with security of supply of oil, gas and power leading to an increasing nationalization of energy production and distribution worldwide. Substantial investments in production capacity and infrastructure are needed in many countries to secure necessary access to energy (IEA 2004, p 32; IEA 2008b, p 39-40).

The Intergovernmental Panel of Climate Change (IPCC 2007a, p 803) has concluded that emission of carbon dioxide to the atmosphere will change the future climate on earth and estimates the atmospheric temperature to increase by 2 to 6^{o} C by the year 2100, which is a tremendous increase from the current average temperature of 17^{o} C.

The Stern review found that ignoring climate change will damage economic growth, creating risks of major disruption of economic and social activity later in this century and in the next, on a scale similar to those associated with the great wars and the economic depression of the first half of the twentieth century. Stern recommends a mitigation investment strategy, where strong action is taken to reduce emissions to avoid severe consequences in the future (Stern 2007, p xv-xix).

The energy market will face at least two major challenges in a 10–20 year perspective. The oil and gas production will reach a point where it cannot meet demand. Secondly the concern about climate damages caused by fossil fuel consumption may lead to incentives to promote the use of CCS and renewable energy. The need for policies to reduce carbon dioxide emission combined with the probability that oil and gas resources within a few decades cannot meet energy demand, represent an opportunity for sustainable energy production.

To understand the future value creation potential in sustainable energy production, it is of particular interest to investigate what sustainability is, the importance of energy to economic development, the energy security situation in a medium- to long-term perspective and the consequences of climate change caused by fossil energy consumption.

2.1 Sustainability

Sustainable development is defined by the World Commission on Environment and Development as "Development that meets the needs of the present without compromising the ability of future generations to meet their needs" (Brundtland 1987). This definition raises at least one fundamental question; how can the world balance the needs of future generations relative to the needs of the present generation?

Herman Daly (1996) views the economy as a subsystem of the ecosystem. Daly (1996) argues that economists and society should recognise that the economy is not exempt from natural laws and that economy cannot be explained by natural laws either. Economic growth can be anti-economic because the marginal physical throughput may cause environmental costs to increase faster than production benefits, thereby making society poorer, not richer (Daly 1996, p 11). Sustainable development would, according to Daly (1996, p 31), mean a change in the current economic norm of economic growth towards qualitative improvement or development as the path of future progress. This would mean a shift towards a steady-state economy where the aggregate throughput of matter and energy is constant.

> Sustainable development necessarily means a radical shift from a growth economy and all it entails to a steady-state economy, certainly in the North, and eventually in the South (Daly 1996, p 31).

Sustainable development means living within local and global environmental constraints. Trade, in a sustainable world, would lead to a situation where some countries try to live beyond their own environmental constraints which would depend on other countries' willingness to limit their own environmental impact (Daly 1996, p 165).

The thermodynamic law of entropy states that the energy and matter in the universe move towards a less useful state. An entropic flow is a flow where matter and energy become less useful. One example is fossil fuels – when fossil fuels are burned to produce energy, the energy itself is not lost, but it is very often turned from useful work to useless heat. The same is true for economies, which are limited by the availability and throughput of matter and energy (Georgescu-Roegen 1971; Reynolds 1999; Daly and Farley 2004, p 29). The expansion of population and physical capital will gradually force humanity to use an increasing share of the production output to handle constraints on environment and natural resources (Meadows, Randers et al. 2005, p xi).

> Eventually so much capital is diverted to solving these problems that it becomes impossible to sustain further growth in industrial output. When industry declines, society can no longer sustain greater and greater output in the other economic sectors: food, services, and other consumption. When those sectors quit growing, population growth also ceases (Meadows, Randers et al. 2005, p xi).

Randers (2000), one of the authors of "Limits to growth – the 30 year update", reflected about the history of sustainable development, and observed that it took nearly ten years after the introduction of the concept of sustainable development in 1986 (Brundtland 1987) for global society to formulate the three elements of sustainable development; financial sustainability, environmental sustainability, and social sustainability. Since the publication of the original "Limits to Growth" in 1972 (Meadows, Randers et al. 1972), Randers (2000) observes that the world has changed from a world constrained by resource scarcity to a world limited by the capacity of the environment to absorb pollution. The Earth has much more fossil fuel than society can burn without causing serious climate change. Randers (2000) concludes that society, and particularly democratic societies, have difficulty facing up to issues where the costs precede the benefits and that achievement of global sustainability is far off. Moxnes (2000) found that the typical political behaviour is to delay necessary protective measures until the development takes an unexpectedly negative turn and becomes severe enough.

> We have learnt that action is slow when the benefits are far in the future, and almost imperceptible when the benefits are also uncertain (Randers 2000).

Economic growth is measured by most economists by measuring gross domestic product (GDP). GDP is a good measure of economic costs, but it is not a good measure of economic development (Dasgupta and Mäler 2001). Increasing environmental costs leads to increased GDP, but could in principle reduce the productive capacity of the society. An improved measure of sustainable economic development should be developed, focusing on the capacity of a nation, region or the world to sustain or maintain productive capacity per capita on a century timescale.

2.1.1 Sustainable economic development

Sustainable economic development can be seen as one of two possible paradigms. The first paradigm is often seen as the **weak sustainability position** assumes that almost all kinds of natural capital can be substituted by man-made capital. The second paradigm, known as **strong sustainability position**, assumes that many of the most fundamental services provided by nature cannot be replaced by services produced by humans or man-made systems. In this view, certain essential natural resources will be lost forever with no substitutes once they are consumed, and the economy will decline as the resource output declines (Tilton 1996; Reynolds 1999; Daly 2005; Ayres 2006). Daly (2005) argues that a strong sustainability position will require a shift from economic growth, which is not sustainable, towards economic development, which presumably is sustainable. The sustainable economy must at some point stop growing, but it does not need to stop developing. Investments in a sustainable world would be mainly for the replacement of capital and qualitative improvement rather than for quantitative expansion (Daly 2005).

Reynolds (1999) found that economic growth can continue without limits if the elasticity of substitution between resources or between capital and resources is sufficiently large and if technologies increase the productivity of resources faster than their exhaustion. However, he also found that the elasticity of substitution for any two inputs must always go to zero, indicating that there are limits to economic growth. Dasgupta and Mäler (2001) found that the economy's productive capacity, and the welfare of the population, is determined by the manufactured capital, human capital and natural capital. Most definitions of sustainable development include the condition that per capita welfare should never decline. This will be satisfied as long as the changes in the aggregate capital, such as natural resources, productive capital and human capital, are positive (Atkinson 2000; Beckerman 2001).

It is, however, as Beckerman (2001) states difficult to see how sustainability and welfare in a distant future should be of any importance for the relatively poor peoples of the world that strive for increased economic welfare and material throughput.

2.1.2 Sustainable energy services

In its report, "World Energy Outlook" for 2006 and 2008, IEA concludes that the world is not on course for a sustainable energy future. In the baseline scenario, IEA finds that CO_2 emissions will be almost two and a half times the current level by 2050. Increasing transport demand will continue to increase the demand for oil, and the carbon intensity of the world's economy is expected to increase due to greater reliance on coal for power generation and production of liquid transport fuels in developing countries with domestic coal resources (IEA 2006a, p 25; IEA 2008b, p 123, 139).

> The world is facing twin energy-related threats: that of not having adequate and secure supplies of energy at affordable prices and that of environmental harm caused by consuming too much of it (IEA 2006b, p 37).

Jaccard (2005) argues that a sustainable energy system must have good prospects for enduring indefinitely in terms of the type and level of energy services it provides while the production and consumption of energy must not exceed the rate at which it can be absorbed by the ecosystem. Jaccard (2005) found that a sustainable energy system will require the development of renewable energy sources, higher energy efficiency, and zero emission fossil fuels combined with a shift in end-use applications towards electricity and hydrogen as energy carriers. Innovations and deployment of these technologies will originate in the most developed economies, and will be driven by emerging market conditions and markets created by government policies (Jaccard 2005, p 318-319; Nuttall and Manz 2008). In a sustainable energy system

> the known, cumulative impacts of the energy system must be negligible and any extraordinary risks it poses must be extremely unlikely (Jaccard 2005, p 11-12).

Security of energy supply is very important for most regions and countries of the world, and it is probably unlikely that a sustainable energy system can be developed without strong emphasis on domestic resources in the energy mix. The most abundant unused energy source, on a short time scale, appears to be coal for many of the large energy-consuming countries. Countries without adequate local energy resources are vulnerable in terms of the security of energy supplies (Ediger, Hosgör et al. 2007).

2.1.3 Sustainable environment

According to Ayres (1996), the developed countries with less than 20 % of the world population consume approximately 80 % of its resources. The current population of 6.5 billion people is expected to increase to around 9 billion by year 2050 (UN 2006). Ayres argues that bringing all these up to a low-to-average middle-class standard of living would imply a fivefold increase in aggregate material and energy consumption which would push the limits of natural resources and the biosphere far beyond sustainability (Ayres 1996).

> Continued economic development is essential; but continued economic development along present lines is ecologically unaffordable (Ayres 1996).

Ayres (1996) found that if the people of the developing world increase their welfare through continued increase in consumption of materials and energy, sustainability would imply that the developed world would have to cut back its aggregate use of material and energy resources by 90 %. This can only be achieved through a reduced living standard, or a change from material demand towards service demand, combined with a sharp increase in the productivity of materials and energy (Ayres 1996). The current economic growth is not sustainable for the indefinite future because of increasing scarcity of materials and energy, and the resulting environmental pollution of a finite environment (Ayres 2001). Daly has suggested three simple rules to help define the sustainable limits to material and energy throughput (from Meadows, Randers et al. 2005, p 54):

- For a renewable resource, the sustainable rate of use can be no greater than the rate of regeneration of its source.
- For a non-renewable resource, such as fossil fuels, the sustainable rate of use should be less than the rate at which a renewable resource can substitute it.
- For a pollutant, the sustainable rate of emission can be no greater than the rate at which that pollutant can be recycled, absorbed, or rendered harmless.

As Nuttall and Manz (2008) describe the challenge, short-term benefits might be outweighed by long-term environmental effects:

> In a world unable and/or unwilling to reduce its carbon footprint, the energy security benefits of increased coal use could be outweighed by a catastrophic climate tragedy: rising sea levels, hurricanes and drought; and the death and destruction caused by these events (Nuttall and Manz 2008).

2.2 Economic growth

Economic growth is the main driver of energy demand and the main cause of environmental pollution. Achieving sustainable economic development will require a stronger coupling between economic theory, natural resources and the capacity of the environment to recycle pollution. The purpose of this section is to describe how economic growth comes about, and how the combined effects of limited energy resources and climate change may limit economic growth. It is important to keep in mind, as Solow (2000) emphasised, that a theory cannot explain everything and that a model will always be a simplified description of the economy. The theory as it is described here is based on the standard neoclassical model, and expanded to include energy supply and climate impact.

> Of course one must not go too far; a theory capable of explaining anything that might possibly be observed is hardly a theory at all (Solow 2000, p 4).

A sustained economic growth rate in per capita GDP of more than 2 % per year is a modern invention. In the years between 1850 and 1950 the growth rate was below 1 %, and before the industrial revolution and the use of fossil energy sources, it was essentially zero (Jones 2002, p 11). Theories of economic growth started with Adam Smith in 1776, who found that growth of output and living standards depended on investment, capital accumulation and labour specialisation. The modern or neoclassical growth theories are based on the work by Solow and Swan which was published in 1956 (Solow 2000). The neoclassical growth theory analysed the role of physical capital accumulation and discovered the importance of technological progress as the ultimate driving force behind sustained economic growth. Paul Romer (1986) and Robert Lucas (1988) tried to fill this gap and developed endogenous growth theories to explain how innovation and human capital contributed to technological progress (Aghion and Howitt 1998, p 7; Jones 2002, p 2; Thirlwall 2006, p 122-164).

In 1958 Nicholas Kaldor summed up six elements that a growth model for advanced industrial economies must be capable of reproducing (Solow 2000, p 7-8):

(1) Real output per person grows at a more or less constant rate.

(2) The stock of real capital grows at a more or less constant rate exceeding the rate of growth of labour input.
(3) The ratio of "real" capital to output is almost constant.
(4) The rate of profit on capital has a horizontal trend.
(5) The rate of growth of output per person can vary widely from one country to another.
(6) Economies with a high share of profits in income tend to have a high ratio of investment to output.

An economy growing according to the first three of these rules is in a "steady state". Its output, employment, and capital stock grow exponentially, and its capital/output ratio is constant (Solow 2000, p 2-3). Solow concluded that:

> The steady state is not a bad place for the theory of growth to start, but may be a dangerous place for it to end (Solow 2000, p 7).

Solow (2000) emphasised that successful theorising is to make the simplifying assumptions in such a way that the final results are not very sensitive. In his Nobel Lecture he stated:

> Naturally I hope that growth theory can serve in both ways: as a background on which to hang multi sector models that probably try to do more than can be done, and as a framework for simple, strong, loosely quantitative propositions about cause and effect in macroeconomics (Solow 2000, p xxvi).

2.2.1 Production function

A closed economy has no flux of labour, capital, energy, materials and knowledge across borders. In an open economy, however, there is flux of all these factors depending on the difference in costs, welfare, trade barriers etc. (Jones 2002; Barro 2004). Theories of economic growth have developed a lot in the last few decades, and endogenous growth theories have contributed substantially to the understanding of how economic growth comes about. Endogenous growth models explain how technological progress develops, and how increased efforts in R&D, human capital and infrastructure contribute to economic growth (Aghion and Howitt 1998; Barro 2004). Solow (2000) found that the three main factors in modelling economic development are:

- Allocation of Capital
- Allocation of Labour
- Technological progress.

The total production of a country is the sum of the production from all the businesses and public services within that country. How a country chooses to distribute its wealth between public and private consumption by use of taxation is not a part of this work. However, the impact of tax and subsidies on the allocation of resources among different energy sources has been investigated. The standard set of neoclassical equations developed by Solow (2000) has been used as the basis for the modelling. Based on the available literature on endogenous growth theory, some elements related to technological progress in the energy sector have been included. The basic growth model is built around two equations; a production function and a capital accumulation equation. The basic equation for production is described by Solow (Solow 2000; Jones 2002, p 22) as a standard Cobb-Douglas production function:

$$Y = F(B, K, L) = BK^{\alpha} L^{(1-\alpha)}$$

where B is the total factor productivity, K is the capital employed and L is the labour force used in production. The value share of capital and labour has been relatively constant over time, with a capital share α of around 0.3 (Fiddaman 1997, p 82; Jones 2002, p 14). The equation show that as capital and labour accumulates, and technology improves, the production output of a society will increase.

2.2.2 Capital

Capital accumulation is one of the major drivers for economic growth in the industrial world, together with human capital and technological progress. Industrial capital in the growth equation refers to the hardware in operation – the machines and factories needed to produce the goods. A fraction of the output from production is used each year to increase the capital stock through investments, expanding the capacity for future production (Meadows, Randers et al. 2005, p 39). Solow assumes a very simple equation for capital accumulation:

$$\dot{K} = \frac{dK}{dt} = sY - dK = I - dK$$

where s is the savings rate, I is the investments and d is the capital depreciation. The savings rate is the fraction of the total production output that is used for investments to accumulate physical capital, typically around 25 %. The depreciation describes how large a fraction of the capital stock that depreciates every year. Assuming that d = 0.05 is similar to an average lifetime of the capital of 20 years, where 5 % of the machines and factories in the model economy wear out each year. The accumulation of capital is therefore dependent on two major factors, the investment of capital and the depreciation of capital.

Energy supplies are essential for utilisation of the industrial capital. A vehicle, for example, needs energy to operate, and without energy, the value of the vehicle for production is in principle zero. The same applies for industrial capital. Economic growth since the industrial revolution has been driven by utilising machines powered by fossil fuels as a substitute for human and animal labour (Ayres 2001; Ayres and Warr 2005). The capital requires a certain amount of energy to perform normal operations, and if this energy is not supplied, the productivity of the capital will be reduced. This can be described and modelled by substituting capital in the growth equation with operating capital (Fiddaman 1997, p 80-88). The simple approach used in this thesis assumes that operating capital can be calculated using the following equation:

$$Ko = K\left(\frac{E_s}{E_R}\right)^{\sigma}$$

where E_s is actual energy supplies and E_R is energy requirement, and σ is the energy-to-capital elasticity. If the energy-to-capital elasticity is zero, there would be no impact of reduced energy supplies to operating capital. A value of one indicates that all capital is equally energy efficient, while a factor between zero and one indicates that the least effective capital will be closed down first in the case of energy shortages.

Depreciation of capital consists of two elements; the normal depreciation of capital due to wear and tear, and depreciation caused by climate change. Depreciation due to climate change describes the amount of destruction and repair/replacement of capital that are required due to damage caused by a changing climate.

The economic model as described in this thesis assumes that energy and man-made capital are complements rather than substitutes. If energy and capital are substitutes, neither of them can be a limiting factor since the productivity of one does not depend much on availability of the other. When they are complements the one in shortest supply is the limiting factor (Daly 1996, p 78).

In the modelling of the coupled energy-economy-climate system in this thesis, it is assumed that the short-term substitution elasticity between energy sources is bound to the type of capital, and it will therefore be close to zero. Since capital and energy are complements, short-term elasticity between capital and energy has to be low. However, it cannot be zero, because this would imply that demand would be independent of price, and that consumption of other goods would be reduced, in principle to zero, to maintain energy consumption. The long-term elasticity is controlled by the replacement of capital, and will be higher than the short-term elasticity (Fiddaman 1997, p 84-87).

As described above, low energy supplies relative to energy requirements will reduce the operating capital and limit production output. Development in energy requirement will be discussed further in the next section.

2.2.3 Energy requirement

Neoclassical economic theory assumes that technological progress creates growth and that resource consumption is a consequence, not a cause, of growth. Economic history shows that the reality is more complex, where it often has been higher-grade energy resources and higher-grade structural resources that have created growth, not just technology alone. The standard economic assumptions and mathematical characteristics of the Cobb-Douglas function implies that energy flows do not contribute much to aggregate productivity and growth (Reynolds 1999; Ayres 2001). Ayres found that the observed economic growth in the USA could be explained almost entirely by substituting technological progress and labour by electric power consumption in the growth equation (Ayres 2001; Ayres and Warr 2005).

Energy requirement is a function of capital multiplied by the average energy efficiency indicator (EEI) as described in the equation below. E_0 is the initial energy requirement and K_0 is the initial capital.

$$E_R = E_0 \frac{K}{K_0} EEI$$

There are three major types of capital that require substantial amounts of energy; transport capital, residential capital and industrial capital.

The transport sector is a very important driver of energy requirements. Over history, a general trend in all regions of the world has been observed, where the passenger distance travelled per capita is equal to 1 km/$ of GDP per capita (Farrell and Kammen 2007b). Slowing this growth in transport demand would require either a substantial reduction in demand for mobility or a shift towards public transportation. Neither is likely to happen unless the fuel prices increase substantially (Turton 2006).

It is difficult to model how energy efficiency in the residential and industry sectors will improve, how fast it will go, and why it will improve. There is a large potential for improvement in energy efficiency by utilising existing technologies, and within a few years there will be new technologies available that can contribute to even larger improvements. However, these improvements will not happen fast due to the embodied energy efficiency in existing capital. Improvements will be driven mainly by the cost of energy and regulations. Today, the energy price seems to be too low for such changes to happen and the short- term environmental cost caused by energy use and pollution is too low to enforce fundamental changes in regulations.

The use of energy efficient technologies will be motivated by price and regulations, and improve faster with higher energy prices caused by market, carbon pricing or energy tax. Energy efficiency is embodied in the capital stock and energy uses are limited by the thermodynamic laws and can never reach zero. As new capital is installed and discarded, the average energy efficiency in the capital adjusts as a co-flow to capital (Fiddaman 1997, p 96).

Energy price seems to be the driver for energy efficiency improvement. Newell et al. (2006) found that the majority of energy efficiency improvements were due to changes in energy prices and changes in energy-efficiency standards, rather than being autonomous. Unander (2004) found that energy efficiency improved across most sectors and countries from 1973 through to the mid to late 1980s, with more modest improvements since then. Unander (2004) concluded that:

> Changes caused by the oil price shock in the 1970s and the resulting energy policies did considerably more to control growth in energy demand and reduce CO_2 emissions than the energy efficiency and climate policies implemented in the 1990s (Unander 2004).

Several studies question the impact of energy efficiency improvements on the total energy consumption due to the rebound effect. The rebound effect can be described as the tendency to use the energy savings to increase consumption of other energy intensive goods or services such as travelling. Frondel et al. (2008) studied the historical rebound effect in Germany and concluded that the effect is approximately 60 %. Jaccard (2005) found that it is unlikely that energy efficiency improvements will stop the primary energy system from expanding almost three-fold towards the end of this century. However, IEA found in their alternative energy scenarios that improved energy efficiency will lead to reduced need for investments in energy supply and is a cheap, fast and environmentally friendly way to meet the world's energy needs (IEA 2006a, p 28):

> Improved energy efficiency in the buildings, industry and transport sectors leads to between 17 % and 33 % lower energy use than in the Baseline scenario by 2050 (IEA 2006a, p 28).

The energy requirement per capital unit will continue to decline as energy losses are reduced or utilised for useful purposes. The energy efficiency improvement rate is mainly a factor of energy cost and capital investments rate, where increasing energy costs and capital turnover will lead to faster decline in energy requirement per capital unit.

2.2.4 Energy demand

Energy demand at low energy prices is equal to the physical energy requirement as described in the previous section. If energy price increases to levels above the marginal productivity of energy, short- term energy demand would be lower than the energy requirement as described in the previous section. Energy demand can be estimated by the equation:

$$E_D = E_R \left(\frac{MPE}{P_e} \right)^{\eta}$$

MPE is the marginal productivity of energy supply, P_e is the energy price and η is the energy demand adjustment coefficient (Fiddaman 1997, p 86). The marginal productivity of energy supply can be derived from the equations described in the previous sections and is:

$$MPE = \frac{dY}{dE_S} = \sigma\alpha \frac{Y}{E_S}$$

An alternative approach to modelling energy demand is described by Webster et al. (2008), who found that energy demand can be described by the equation:

$$E_D = E_{D0}\left(\frac{P_e}{P_{e0}}\right)^{\beta}\left(\frac{GDP}{GDP_0}\right)^{\theta} \Rightarrow \frac{E_D}{E_{D0}} = \left(\frac{P_e}{P_{e0}}\right)^{\beta}\left(\frac{GDP}{GDP_0}\right)^{\theta}$$

The parameters with subscript 0 refer to a reference or initial value of modelling. Webster et al. (2008) found that the price elasticity of energy β is -0.23 and the income elasticity θ is 0.34 for the US economy (Webster, Paltsev et al. 2008). The income elasticity reflects the energy improvements in production capital, as increased GDP will require more capital with associated energy needs. This equation indicates that doubling of energy price due to market or CO_2 costs would reduce the energy demand by 15 %. Testing of both models in the CE2 simulation model developed in this thesis give approximately similar energy demand.

2.2.5 Technological progress

Solow (2000) found that technological progress is the dominant engine of growth which explains about 80 % of the economic growth in modern economies. While Solow (2000) regarded technical progress as an exogenous factor, others, such as Romer (1986) and Lucas (1988), consider it to be endogenous to economic growth (Isoard and Soria 2001), and Ayres and Warr (2005) found that it could be explained almost entirely by energy input. Most models of climate change assume an exogenous overall productivity growth of about 2–3 % per year (Löschel 2002). Solow (2000) concluded that technological progress finds its way into production through the use of new and different capital equipment, and that this mechanism is omitted from his growth model. Therefore, policies to increase investment would lead to faster transfer of new technology and affect growth rates. Solow (2000) noticed that: "It appears that the ones that invested fastest were best able to take advantage of the available knowledge" (Solow 2000, p xxiii).

Many researchers have concluded that innovation and entrepreneurship should have a stronger position within macroeconomic theory. Landstöm (2005) stated that the dominating macroeconomic theory based on economic equilibrium does not include entrepreneurship as a driving force, while this was a central driving force for economic development in Schumpeter's economic theories (Landström 2005, p 49-50). Schumpeter recognised that:

> The ruling paradigm of the economics of development rests on the classical-neoclassical view of a world in which change is gradual, marginalist, non-disruptive, equilibrating, and largely painless (J. B. Nuggets and P. A. Yotopoulos quoted in Schumpeter 1934, p l).

Porter (1990) stated that: "The doctrine that is embedded in classical economics is at best incomplete and at worst incorrect". Lazonick (2003) found that the theory of market economy lacks an explanation of the successful growth of the wealthy economies, leading to a tendency to see developed markets in labour, capital and products as causes rather than consequences of economic development. Stiglitz (1987) emphasised the importance of technological progress in traditional economic theory when he stated that:

> in the long run the growth rates in all countries should be related only to the rate of technological progress (Stiglitz 1987).

Endogenous growth theories try to explain and model the factors within the economy that drive technological progress. In the Romer (1986) model, technological progress is modelled by a quite simple equation where the labour force is divided into R&D labour and production labour, where the contribution of R&D labour to technological progress is modelled. The Lucas (1988) model tries to explain technological progress through the development of human capital, rather than input of labour force alone (Jones 2002, p 100). Solow (2000, p 102) argues that an endogenous growth theory needs to be based on serious analysis of the determinants of innovation and technological process, but Solow (2000, p 123) sees difficulties in making a good model. However, Solow (2000, p 180) thinks it is a mistake to divide growth theory into an "exogenous" and an "endogenous" branch because every economic theory will have to stop somewhere and rest on some exogenous elements.

Endogenous growth is relevant for modelling technological progress. However, when trying to understand the energy supply system, or impacts of climate change, the focus is on energy supplies to support economic growth or technological progress. For modelling of the energy system, an exogenous approach as described by Fiddaman

(1997, p 83) seems to be sufficient for generating scenarios with respect to energy demand. Endogenous growth theories are useful for understanding the mechanisms for technological progress in the energy sector and discussing prioritisation of limited R&D resources between different energy sectors.

2.3 Energy security

Energy supplies works as the blood in the economy and reliable energy supplies are necessary to secure economic development and the welfare of the population in all nations. To secure the welfare of the population in Norway and Europe, reliable energy supplies are required.

In World War I, Sir Winston Churchill made the decision to shift the power source of the British navy's ships from coal to oil to make the fleet faster than the German fleet. This switch from domestic coal to insecure oil supplies from Persia lifted energy security to a national strategic issue. Churchill's response to this challenge was: "Safety and certainty in oil, lie in variety and variety alone" (Yergin 2006).

The usual definition of energy security is simply availability of sufficient supplies at affordable prices (Yergin 2006). IEA (2006a) conclude in their scenario analysis that:

> Secure, reliable and affordable energy supplies are fundamental to economic stability and development. The threat of disruptive climate change, the erosion of energy security and the growing energy needs of the developing world will pose major challenges for energy decision makers (IEA 2006a, p 25).

In his State of the Union address in 2006, the US President George W. Bush stated that keeping USA competitive requires affordable energy, and he announced that the country had a serious problem: "America is addicted to oil, which is often imported from geopolitical unstable parts of the world. The best way to break this addiction is through technology" (Bush 2006).

President Bush stated that the goal of the US is to replace more than 75 % of the oil imports from the Middle East by 2025 (Bush 2006). The Swedish government has also decided to be independent of imported oil within 2025, and is currently investing a lot of effort on the development of bio energy (Persson 2006). The current focus on energy security is driven by a tighter oil market and by increasing oil prices (Yergin 2006). During the last decade there has been a large increase in the demand for oil, mainly driven by the economic growth in China and India. These countries have changed from self-sufficiency to a dependence on global energy markets, and they are concerned about their increasing cost of energy imports. According to Yergin (2006), future energy supplies will be constrained by international affairs, politics, energy investment and new technological development. Yergin (2006) found that there are four principles to maintain energy security:

1. Diversification of supply.
2. A "security margin" in the energy supply system.
3. Stability in the global market.
4. Open information flow for a well-functioning market.

Energy security is even more important in times of war than in peace. Lack of domestic energy resources would require substantial energy storage capacity, combined with alliances with energy-rich countries to secure the energy supplies to the military force in case of a war situation (Economides and Oligney 2000). In the State of the Union address in 2008, President Bush included the environmental challenges in the energy security challenge.

> To build a future of energy security, we must trust in the creative genius of American researchers and entrepreneurs and empower them to pioneer a new generation of clean energy technology. Our security, our prosperity, and our environment all require reducing our dependence on oil (Bush 2008).

There is reason to be concerned about security of energy supplies in North America, Europe and Asia Pacific, where the economic growth is based on a relatively high fraction of imported energy (BP 2007). Europe imports about half of its energy consumption and is very reliant on Russia, North Africa and the Middle East as energy providers. North America and the Asia Pacific regions import about one-quarter of their energy consumption and will become more dependent on energy imports as the economy and energy requirement expands (BP 2007). Nordhaus and Boyer (2000, p 53-55) conclude that if fossil fuel supplies are relatively price-inelastic as seen in recent years, i.e. supplies will not increase significantly due to price increases, then carbon-energy prices will rise sharply as the limits of these resources are reached. The significant energy price increases in the last few years may indicate that the global energy supply approach these limits, which will be discussed further in the survey of global energy resources in the next section.

2.3.1 Energy resources

This section will present a survey of the energy resources available in the twenty-first century, both fossil fuels and renewable energy, as seen today. The total energy system can be defined as the "combined processes of acquiring and using energy in a given society or economy" (Jaccard 2005, p 6).

The definition above includes the different sources of primary energy and the secondary energy that these primary sources are transformed into (Jaccard 2005, p 6). In this transformation from primary to secondary energy, such as electricity, and finally to useful work, there is an energy loss of approximately 86 % (Ayres and Warr 2005). The vast majority (95 %) of the current world commercial primary energy consumption is based on fossil fuels such as coal, gas and oil. The regional numbers show some differences reflecting the regional differences in energy availability (BP 2007).

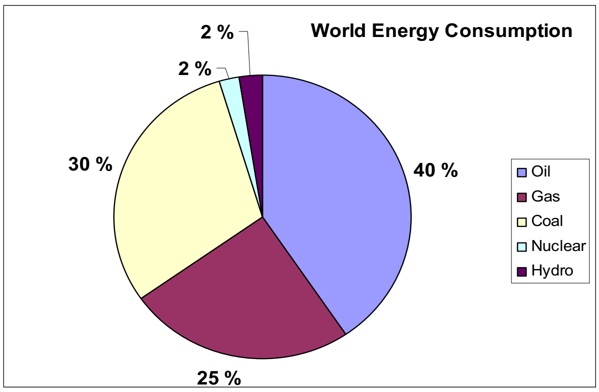


Figure 4: World Primary Energy Consumption is to a large extent based on fossil fuels, with 95 % of commercial energy consumption is based on oil, gas and coal (BP 2007).

IEA's World Energy Outlook 2008 (2008b, p 38) concludes that the world's energy need will be almost 45 % higher in 2030 than they are now. According to IEA and CERA (Yergin 2006, p 74-75), the Earth's fossil energy resources are sufficient to meet demand until 2030. They find that the global production of conventional oil will not peak before 2030 if necessary investments are made. An increasing share of future supplies is expected to come from "non-traditional oils" such as ultra-deep waters, oil sands, natural gas liquids, gas-to-liquids, coal-to-liquids, etc. (Esser 2005).

2.3.1.1 Fossil energy sources

Reserves are generally defined as proven resources, while the quantity of resources includes undiscovered resources that are expected to be found. The remaining global reserves of conventional oil have been stable around 1200 billion barrels during the last few years due to increases in recovery and new discoveries that compensate for oil extraction. Most literature sources estimate the oil resources to be two to three times the amount of the estimated reserves (BP 2007; WEC 2007; IEA 2008b).

Unconventional oil such as oil shale and extra-heavy oils occurs in large volumes in relatively few locations. Oil shale is mainly located in the USA and Russia, with an estimated total in-place volume of 2800 billion barrels. However, the cost of extracting oil from oil shale is high and the current expected recovery is low. Extra-heavy oil is mainly located in Venezuela and Canada, with a total in-place volume of 5500 billion barrels. The production of these volumes requires large amounts of steam to heat the oil to make it flow, which consumes 10–40 % of the total primary energy output. In total, a recovery of up to 10–20 % can be expected from these resources (WEC 2007, p 120-129).

Several authors, such as Simmons (2005) and Aleklett (2006), argue that the world oil production are close to a peak, and that world oil production will start to decline within a few years. They argue that the remaining reserves, especially in the Middle East, will be insufficient to supply the world with the growing need for energy. This is a reasonable conclusion, based on reserves numbers alone. However, if resources are included the picture changes fundamentally. Reserves are estimated based on expected recovery from discovered resources, with current recovery methods, and should be considered as a pessimistic estimate. If the undiscovered resources and unconventional oil are included, resources which are highly uncertain, the picture will be different. Based on reserves figures from the BP statistical review (2007), resource figures from IEA (2004, p 94) and reserves and resource figures from World Energy Council (2007), low, medium and high estimates have been established for remaining resources. These figures are listed in table 1 and 2 below. In "World Energy Outlook 2008", IEA (2008b, p 205) has published a more comprehensive update of resource estimates and production forecasts, giving slightly higher oil resource numbers than those presented here, which could defer peak petroleum by approximately five years.

Table 1: Conventional oil reserves and resources at the end of 2006

	Conventional Oil					Total Oil Resources			Total Remaining Oil Resources		
	Production Rate	Cumulative Production	Remaining Reserves	Additional Resources	Total	Low	Medium	High	Low	Medium	High
	mill bbl/day	bill bbl	bill bbl	bill bbl	bill bbl	bill bbl	bill bbl	bill bbl	bill bbl	bill bbl	bill bbl
North America	13,7	209	59,9	50	318,9	270	290	320	61	81	111
Latin America	6,88	75	103,5	50	228,5	180	200	230	105	125	155
Europe	2,4	36	7,1	4	47,1	43	47	50	7	11	14
Norway	2,78	22	8,5	5	35,5	30	35	40	8	13	18
Eurasia (FSU)	12,3	147	128,9	200	475,9	275	375	475	128	228	328
Middle East	25,59	277	742,7	300	1319,7	1000	1150	1350	723	873	1073
Africa	9,99	96	117,2	200	413,2	210	310	420	114	214	324
Asia Pacific	7,94	83	40,5	20	143,5	120	135	150	37	52	67
Total	81,58	945	1208,3	829	2982,3	2128	2542	3035	1183	1597	2090

Table 2: Unconventional oil reserves and resources at the end of 2006

	Unconventional Oil					Total Unconventional Oil Resources			Total Remaining Unconventional Oil Resources		
	Production Rate	Cumulative Production	Remaining Reserves	Additional Resources	Total	Low	Medium	High	Low	Medium	High
	mill bbl/day	bill bbl	bill bbl	bill bbl	bill bbl	bill bbl	bill bbl	bill bbl	bill bbl	bill bbl	bill bbl
North America	1	5	200	500	705	200	400	705	195	395	700
Latin America	0,6	15	250	500	765	250	450	765	235	435	750
Europe	0	1	0	0	1	1	1	1	0	0	0
Norway	0	0	0	0	0	0	0	0	0	0	0
Eurasia (FSU)	0	1	70	100	171	70	100	171	69	99	170
Middle East	0	0	0	0	0	0	0	0	0	0	0
Africa	0	0	0	0	0	0	0	0	0	0	0
Asia Pacific	0	0	40	0	40	40	40	40	40	40	40
Total	1,6	22	560	1100	1682	561	991	1682	539	969	1660

Based on these figures for resources, oil production profiles have been established as illustrated in figure 5. The basic formula assumes that the production of conventional oil increases by 7 % per year until 40 % of the total resources are produced. Then it is assumed that oil production will decline at a rate of 7 % from the point where more than 50 % of the total resources are produced. The most pessimistic view would be to base the production estimates on the reserves only, while a more optimistic view would be to include the figures for resources. Unconventional oil is more difficult. There are enormous resources in the ground, but they are technologically difficult and economically expensive to produce. It is assumed that the production of unconventional oil can be increased by 7 % per year until 20 % of the total resources are produced and that unconventional oil production will decline at a rate of 5 % when more than 40 % of the total resources are produced. This gives a continued increase in production of unconventional oil in the entire period, reaching a maximum level of 17 million barrels per day in 2046. Figure 5 shows a low estimate of future oil production, based on reserves only, on the left and a high estimate on the right based on resource numbers.

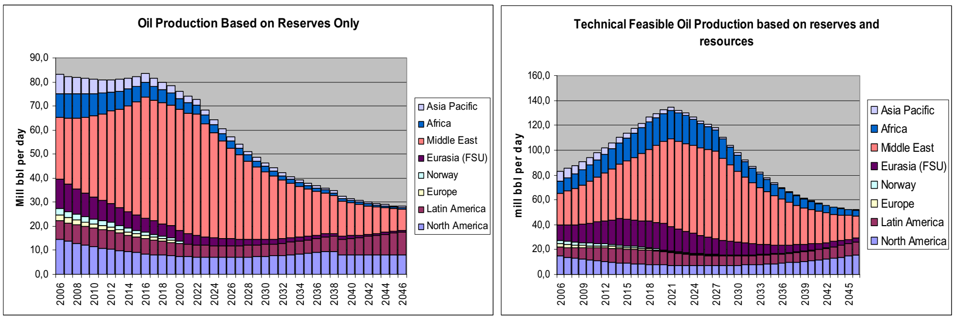


Figure 5: Estimated future oil production based on reserve and resource estimates

Figure 5 above demonstrate several important points:

- Continued investment in increased capacity in the Middle East will be important for continued increase in oil supply.
- The world will approach a peak in oil production within two to three decades.

Predicting the peak of oil production is difficult due to the poor quality of world oil resource estimates and political instability in oil supply regions, which has a serious impact on the oil production output (Belhaj and Lay 2008). Greene et al. (2006) found that the peaking of conventional oil production is almost certain to occur within the next two decades and deserves immediate and serious attention to prepare for the transition to other energy sources. IEA found that the increase in oil prices in the last five years have not resulted in significant reductions in global demand or increases in oil production and that current investments will be insufficient to replace declining oil production (Mouawad 2008). Fatih Birol, the chief economist at the International Energy Agency in Paris concluded that:

> According to normal economic theory, and the history of oil, rising prices have two major effects, they reduce demand and they induce oil supplies. Not this time (Mouawad 2008).

The global oil supply from non-OPEC sources is expected to decline and these will probably become less relevant for the global oil supply (Iledare and Pulsipher 1999). As the world approach the "peak oil" situation, society will learn that past "energy crisis" experience will be insufficient, mainly because the "peak oil" situation will create a severe shortage of liquid fuels for the transportation sector and result in dramatically higher oil prices, causing economic stress in the major oil-importing nations. Government intervention to secure production of large amounts of substitute energy will be required to avoid the economic and social implications of oil peaking (Hirsch, Bezdek et al. 2005, p 64-67).

The gas resources used in this study are estimated based on BP and World Energy Council (WEC) figures, and are listed in table 3 below (BP 2007; WEC 2007, p 160-163).

Table 3: Gas reserves and resources at the end of 2006

	Gas					Total Gas Resorces			Total Remaining Gas Resources		
	Production Rate	Cumulative Production	Remaining Reserves	Additional Resources	Total	Low	Medium	High	Low	Medium	High
	BCM/day	TCM	TCM	TCM	TCM	TCM	TCM	TCM	TCM	TCM	TCM
North America	754,4	25	7,98	4	36,98	33	35	40	8	10	15
Latin America	144,5	2,25	6,88	4	13,13	9	12	15	6,75	9,75	12,75
Europe	202,7	7,4	2,43	1	10,83	10	11	12	2,6	3,6	4,6
Norway	87,6	1,1	2,89	1	4,99	4	5	6	2,9	3,9	4,9
Eurasia (FSU)	779,3	20,3	58,1	40	118,4	80	100	120	59,7	79,7	99,7
Middle East	335,9	4,3	73,47	20	97,77	80	90	100	75,7	85,7	95,7
Africa	180,5	2,4	14,18	20	36,58	16	25	40	13,6	22,6	37,6
Asia Pacific	377,1	5,7	14,82	15	35,52	20	30	40	14,3	24,3	34,3
Total	2862	68	181	105	354	252	308	373	184	240	305

Production profiles based on these reserve and resource estimates indicates an increasing production, particularly in Russia, the Caspian region and the Middle East, with a peak production output around 2030 of between 3.5 and 6 Trillion Cubic Meter (TCM) per year (ref figure 6). The market share of gas will probably increase in the next few decades as gas becomes more important as an energy source. The Middle

East, North Africa and Eurasia (FSU) will play a significant role in the future gas supply to Europe (Al-Fattah and Startzman 2000).

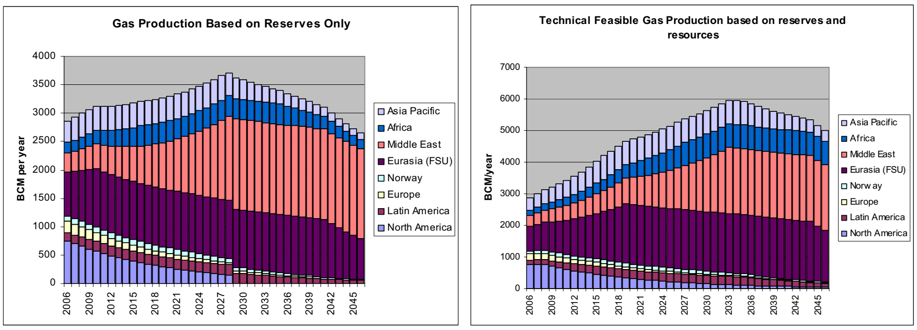


Figure 6: Expected gas production based on reserve and resource numbers

The exponential growth of energy demand will cause unforeseen problems for most of us. The illustration below is taken from "Limits to Growth – the 30 year update" (2005) and is an excellent example of the consequences of exponential growth.

> In 2000 the world reserve-production ratio for natural gas was 65 years, which means that if current known reserves continued to be used at 2000 consumption rates, they would last until the year 2065. Two things will happen to make that simple extrapolation wrong. One is that more reserves will be discovered. The other is that gas use will grow above the 2000 rate (…) Suppose, for purposes of illustration, that the gas resources in the end will prove sufficient to supply the world at the 2000 usage rate for 260 years (…) If gas consumption continues to grow as it has since 1970, at about 2.8 percent per year, the 260-year resource endowment would plummet exponentially. It would be exhausted not in 2260, but in 2075; it would last not 260 but only 75 years. The point is not that the world is about to run out of natural gas. The considerable resources that remain will be essential as a transition fuel on the way to more sustainable energy sources. The point is that fossil fuels are surprisingly limited, especially when used exponentially and they should not be wasted (Meadows, Randers et al. 2005, p 93-95).

Coal resources are generally thought of as abundant, allowing for increased coal consumption far into the future, enabling substitution of declining crude oil and natural gas supplies which could potentially lead to catastrophic consequences for the world's climate. The quality and extent of coal resources are poor, both on global and national levels. The energy watch group (2007) concluded that global coal reserves are concentrated in six countries; the USA, Russia, India, China, Australia and South Africa, of which the USA has 30 % of all reserves and is the second largest producer. China is the largest producer but possesses only half the reserves of the USA. Most coal extracted (85 %) is consumed domestically. Global coal production may increase by about 30 % until it stabilises around 2020 (Zittel and Schindler 2007, p 4-6). Security of supply are significant incentives for continued use of coal in the USA, China, India and Europe, even in a carbon-constrained world (Ansolabehere, Beer et al. 2007). Coal resources are estimated based on BP and WEC figures and are listed in table 4 below (BP 2007; WEC 2007, p 9-21). The coal resources might be as much as five to ten times higher than estimated in this thesis, which would cause a major climate problem for society if the CO_2 were emitted to the atmosphere.

	Coal					Total Coal Resorces			Total Remaining Coal Resources		
	Production Rate	Cumulative Production	Remaining Reserves	Additional Resources	Total	Low	Medium	High	Low	Medium	High
	mill ton/yr	bill ton	bill ton	bill ton	bill ton	bill ton	bill ton	bill ton	bill ton	bill ton	bill ton
North America	1128	75	254,4	200	529,4	330	430	530	255	355	455
Latin America	81	3	19,9	5	27,9	25	27	30	22	24	27
Europe	603	70	38	0	108	110	111	112	40	41	42
Norway	0	0	0	0	0	0	0	0	0	0	0
Eurasia (FSU)	490	50	227	35	312	280	300	320	230	250	270
Middle East	0	0	0	0	0	0	0	0	0	0	0
Africa	262	15	50,7	0	65,7	65	66	70	50	51	55
Asia Pacific	3511	150	297	120	567	450	500	600	300	350	450
Total	6075	363	887	360	1610	1260	1434	1662	897	1071	1299

Table 4: World Coal resources

Production profiles (ref figure 7) indicate that coal production can increase significantly over the next 25 years if the energy demand continues to grow as expected and if there is a need to substitute oil and gas production. Coal will probably remain important with respect to energy security in Asia, North America and Europe.

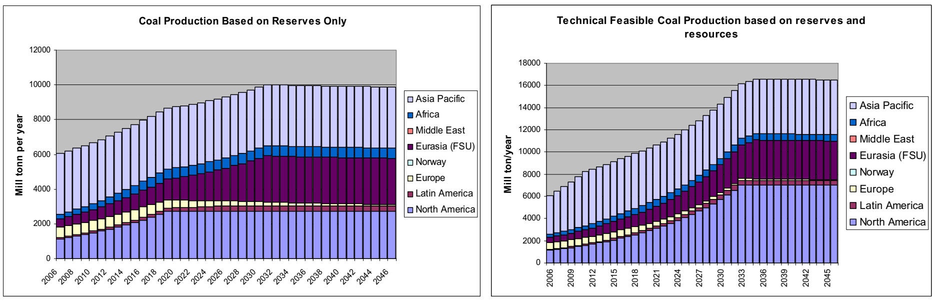


Figure 7: Expected future coal production potential based on reserves and resource estimates

Stern (2007) concludes that there are enough fossil fuels to meet world consumption demand at a reasonable cost until 2050 as illustrated in figure 8. Stern finds that a large increase in real fossil fuel prices is not necessary to increase supply. However, price increases through energy or carbon tax would be necessary to limit energy demand and emissions growth (Stern 2007, p 212-213).

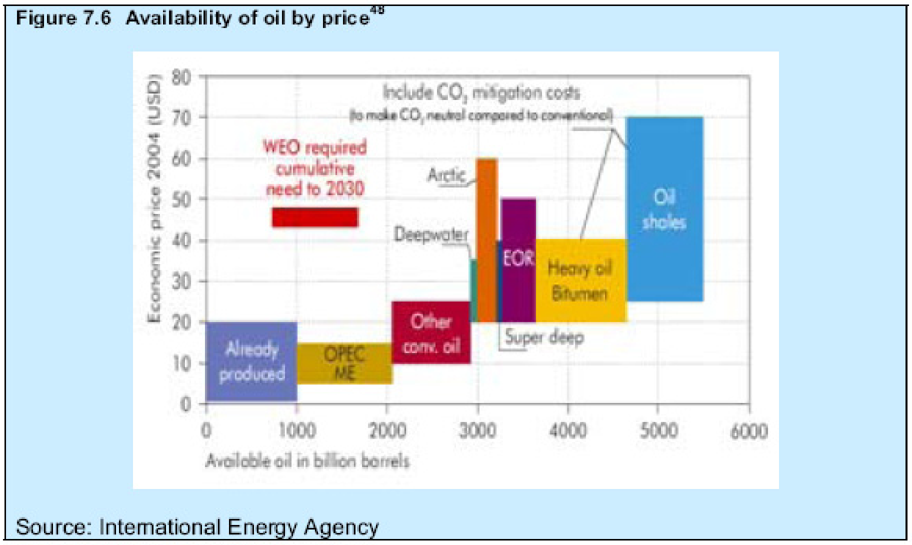


Figure 8: Availability of oil by price (Stern 2007, p 212).

Brandt and Farrell (2006) found that significant amounts of liquid fuels could be produced at reasonable cost by use of enhanced oil recovery and gas- and coal-derived synthetic liquid fuels. However, this would create an increasing greenhouse gas emissions per energy unit, as illustrated in the lower part of figure 9, where emissions are separated into fuel combustion and production and processing emissions by a dashed line. The increased cost in petroleum development has been large during the last five years following the increase in oil price. StatoilHydro expects that the cost of tar-sand production in Alberta would be around $80 per barrel (Løvås 2008), a cost level which is 150–200 % higher than the estimates of IEA (Stern 2007, p 212-213) and Brandt and Farrell (2006), above.

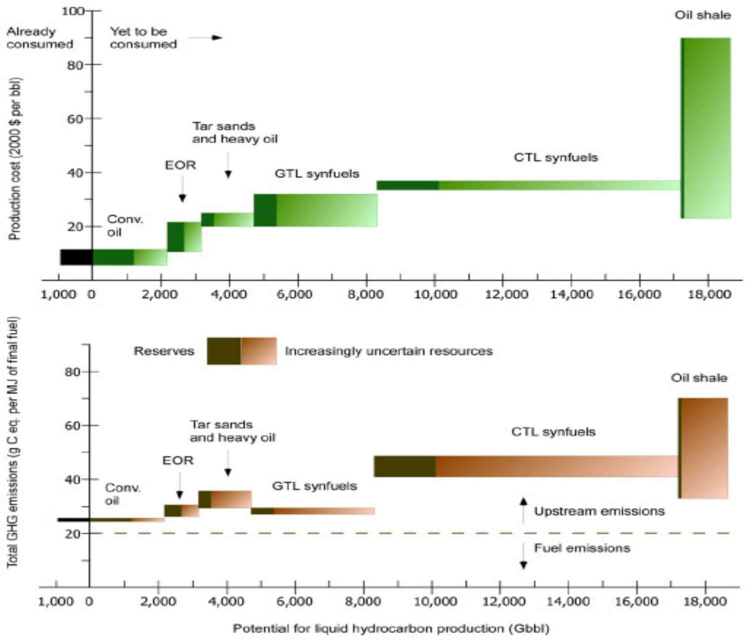


Figure 2: Global supply of liquid hydrocarbons from all fossil resources and associated costs in dollars (top) and GHG emissions (bottom) (Farrell and Brandt 2006).

Currently, alternatives to conventional oil, such as unconventional oil, gas-to-liquid and coal-to-liquid are relatively more expensive, but as these sources are developed, economies-of-scale and economies-of-learning could result in substantial cost reductions. In the North Sea, oil production costs decreased from $35 to $15 per barrel from the late 1970s to 1990 due to learning (Jaccard 2005, p 157).

2.3.1.2 Renewable energy resources

The renewable energy potential in the world is large but relatively expensive compared with current fossil fuels. This will change, however, as the renewable industry gain experience and improve the technologies. The main renewable energy sources are; biomass, bio-fuels, hydro power, wind power and solar power.

Biomasses are mainly used as a non-commercial energy source for heat generation for residential purposes, but also as a commercial fuel for centralised heat production and distribution. Biomass is probably the main energy source for the population in the developing world (Jaccard 2005, p 23), and an important energy source in many developed countries such as Norway. Due to the large, non-commercial volume of biomass production and use, reliable records of the volumes involved are not available. Biomass is a sustainable source of energy which reduces greenhouse gas emissions because the energy comes from plants which take a similar amount of carbon dioxide out of the atmosphere as they release when they are burned (Pittock 2005, p 177). The global potential for biomass energy production is only sufficient to replace a few percent of current fossil-fuel usage without reducing food security and exacerbating climate change (Field, Campbell et al. 2007).

Bio-fuels are liquid or gaseous fuels for transport purposes produced from biomass, which may be pure bio-fuels for dedicated vehicles, or a blend of bio-fuels and fossil fuels that can substitute for conventional motor fuels (Demirbas 2008). Farrell found that by using current technologies, it is possible to push the bio-fuel fraction of transportation fuel up to 2–3 %, while market shares beyond that would have to be based on different technologies. In the United States, roughly 23 % of the current corn crop is used for ethanol production which in turn provides 3 % of the nation's transportation fuels (Tollefson 2008). In its Alternative Policy Scenario, IEA found that bio-fuels could account for 7 % of the road-fuel consumption in 2030 compared with 1 % in 2008. IEA commented that:

> Rising food demand, which competes with bio-fuels for existing arable and pasture land, will constrain the potential for bio-fuel production using current technology (IEA 2006b, p 44).

Hydro power is the main electricity source in Norway and accounts for approximately 99 % of the electricity production (WorldBank 2006). Worldwide, hydropower generated 2800 TWh of electrical power in 2005. The total technical potential is estimated to 16000 TWh, where half of the potential is considered to be economically feasible at current electricity prices. The potential is, naturally, largest in areas with a lot of water and high mountains such as Brazil, Congo, Canada, the USA, China, India and Russia (WEC 2007, p 279-283).

The global economic potential of wind power is estimated at between 20000 and 40000 TWh per annum (Pittock 2005, p 175), which is substantial compared with the current worldwide electricity consumption of 15000 TWh per year (IEA 2007, p 92-93). The potential is probably significantly higher if the potential of offshore wind is included. The technical potential for offshore wind power in Norway is estimated to 14000 TWh per year (ENOVA 2007), approximately equal to the current global electricity consumption. The cost of offshore wind production, where the wind force is higher and more stable, and the turbines can be larger, is expected to be below $ 0.10/kWh within a few decades, which would be comparable with solar power (Gether 2007). The total electricity production from wind power at the end of 2006 was 160 TWh per year, of which 70 % was produced in Europe, mainly in Germany, Spain and Denmark, and 20 % in the USA (WEC 2007, p 479-488).

Solar energy has a substantial technical potential, estimated to be four times current global energy consumption. However, at present the cost of generating electricity from photoelectric solar cells is not competitive with fossil fuels, except in areas not served by electricity distribution systems (Pittock 2005, p 173). Japan, Germany and the USA are currently the main producers of solar energy, with almost 80 % of the global production. The total output is approximately 7 TWh per year and increases by 40 % per year (WEC 2007, p 387).

The main problem with renewable energy sources today, except for hydro power, is that they are more expensive than fossil-fuel power. The average European electricity price in 2008 was approximately $ 0.09/kWh (Nordpool 2008). Solar-PV currently has a cost between $ 0.20/kWh and $ 0.30/kWh (WEC 2007, p 387-392), but is expected to be produced at costs below $ 0.10/kWh in 2050 due to technological development (Vries, Vuuren et al. 2007). “The combined potential of the wind-solar-biomass options can in most regions supply future electricity demand at costs below 0.10 $/Kwh” (Vries, Vuuren et al. 2007).

One challenge for wind and solar power is that output does not necessarily match demand, which requires electricity storage for later use when there is insufficient base load to supply the need. This effect could be resolved by investments in improved distribution systems, allowing for longer electricity transport and by energy storage in hydropower dams, compressed air and hydrogen. Some of the base load needs to be provided by traditional power plants or geothermal energy. Tester et al. (2006) found that geothermal energy can provide 800 TWh per year of base-load electric power and heat in the United States with minimal environmental impacts. The global geothermal energy production was 130 TWh/year in 2004 (WEC 2007, p 427).

Enormous amounts of renewable energy are available worldwide, but currently most renewable energy production is too expensive to produce and distribute to be able to compete against fossil fuels. The challenge in terms of creating a sustainable energy system is to reduce the costs of renewable energy sources fast enough to make it competitive against coal power as the world approach "peak petroleum", to avoid a "lock-in" to coal power.

2.3.1.3 Nuclear energy

Nuclear energy has been high on the political agenda lately as a climate-friendly solution to the energy challenge. Nuclear electricity generation was 2600 TWh in 2005, supplying approximately 16 % of the world electricity consumption. At the beginning of 2007 there were 435 plants, with almost 300 located in the main producing countries; Japan, Korea, the USA, Russia, Germany and France (WEC 2007, p 235). Deutch et al. (2003) concluded that it is technically possible to expand current worldwide nuclear capacity to 8000 TWh by the year 2050, which could reduce annual carbon dioxide emissions from coal plants by 1.8 billion tonnes compared with a business-as-usual scenario. However, Deutch et al. (2003, p ix) found that in a deregulated market, nuclear power is not cost competitive with coal and natural gas. Zittel et al. (2006) highlight two important aspects related to the development of nuclear power in the next decades; the supply of uranium and the addition of new reactor capacity. Zittel et al. (2006) finds it unrealistic to believe that nuclear breeding reactors or thorium reactors will play a significant role in the next few decades. They found that the discovered uranium reserves are sufficient for 30 years of supply, and if estimates of undiscovered resources from the Nuclear Energy Agency are included, the possible resources would double or at best quadruple (Zittel and Schindler 2006, p 4). With exponential growth in nuclear power output, it is unlikely to expect uranium resources to last more than 30 years. IEA (2006a; 2008b) expects nuclear output to be almost constant towards 2030 because of "their large capital cost; public opposition due to the perceived threats of radioactive waste and nuclear accidents; and the possible proliferation of nuclear weapons" (IEA 2006a, p 29).

Storing nuclear waste is a major environmental problem related to nuclear power, and if society applies the precautionary principle to nuclear waste, as it intends to do with CO_2 emissions. Society should, as Jaccard argues, avoid producing such waste until it has a solution to safely handle the waste materials.

> The assumption that humans can safely handle radioactive waste seemed arrogant. Leaving a stockpile of such material for others to deal with went completely against my values of taking responsibility for one's impact on the earth and one's obligations to future generations (Jaccard 2005, p 2).

Motivated by the significant national thorium resources in Norway, Kara et al. (2008) studied the potential for utilizing thorium reactors in Norway and concluded that development of a thorium reactor currently is not within the capability of Norway. Kara et al. (2008) found that:

> The current knowledge of thorium-based energy generation and the geology is not solid enough to provide a final assessment regarding the potential value for Norway of a thorium-based system for long term energy production (Kara, Kullander et al. 2008).

Nuclear fusion could be an option in the latter part of the twenty-first century, with far less radioactive waste, if feasibility can be demonstrated in the next few decades (Pittock 2005, p 173). Nuclear fusion could potentially be game changing in the energy market, but will not be a commercial option for the next 40–50 years (ITER 2005).

Nuclear power is not a sustainable energy source because of two main factors; the limited nuclear fuels available and the environmental issues related to storing nuclear waste.

2.3.2 Energy distribution infrastructure

The expansion of energy consumption will require massive investment in energy-supply infrastructure. A shift from liquid fuel to electricity in the transport sector would reduce the total primary energy consumption, but increase the need for investments in electricity distribution. The positive side of such a shift in the transport sector is that it could lead to smoother electricity consumption during the day, utilising the low demand periods during night time for the charging of vehicles. Electrification of transportation gives the opportunity to utilise existing distribution infrastructure, compared to hydrogen as an energy carrier which would require investments in a new distribution infrastructure. IEA estimates that a cumulative investment of just over $26 trillion is required in the period 2008–2030, of which the power sector accounts for 56 % and oil investment accounts for 20 %. More than 50 % of these investments are expected to be in developing countries. IEA (2006b, p 40; 2008b, p 39) questions the willingness and ability of major oil and gas producers to invest such amounts due to “shortages of skilled personnel and equipment, regulatory delays, cost inflation, higher decline rates at existing fields and geopolitics”.

A large market share for solar and wind energy may create challenges in the distribution system because the distribution grid is not designed for moving large amounts of electric power from a sun- or wind-rich location to the energy consuming cities. It is generally designed for local distribution (Wald 2008). Large volumes of solar power and wind power in the energy supply chain will require solutions for electricity storage.

Typical energy loss in the distribution system is in the order of 5–10 % for both fossil fuels and electricity. This loss is due to friction in oil and gas pipelines requiring compression, fuel consumption for transporting fuels from one location to another, and electric resistance in power cables leading to heat loss.

2.3.3 Power production facilities

IEA (2007) expects that the global electricity demand will double in the next 25 years, reaching 30,000 TWh/year in 2030. In 2005, IEA (2007) estimated that 40 % of the global electricity generation was in coal-fired power plants, 20 % in gas-fired power plants, 7 % from oil-fired power plants, 16 % from hydro power, 2 % from non-hydro renewable, and 15 % from nuclear power. IEA (2007, p 92) expects coal, gas and non-hydro renewable to increase their market shares towards 2030. Figure 10 illustrates the current challenge related to power production. However, in the next 25 years, half of existing production capital will be replaced due to depreciation. Investments in new capital would be twice the existing capital, meaning that three-quarters of the power generation capital in 2030 has not yet been constructed, and could in principle be renewable energy production.

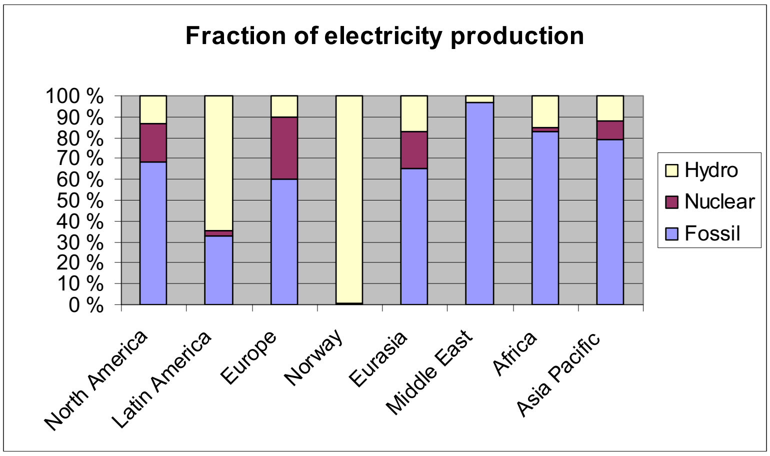


Figure 10: Sources of electricity generation (BP 2007).

The electric generating efficiency of coal-fired power plants averaged about 35 % in 2003, and for gas-fired power plants the electric efficiency averaged 42 %, with a range from 33 % in Russia to 49 % in Western Europe, where combined-cycle gas turbines has been introduced (IEA 2006a, p 178). Integrated coal gasification combined-cycle (IGCC) plants are expected to achieve efficiencies above 50 % within ten years, while combined cycle gas turbines (CCGT) can approach 60 % (Jaccard 2005, p 186; IEA 2006a, p 180-181). Adding CO_2 capture and storage (CCS), which is energy intensive with current technologies, would result in a 10–30 % increase in coal and gas consumption to produce the same amount of electricity. Current CCS design gives a 39 % increase in fuel consumption and 85 % reduction in CO_2 emissions (IEA 2006a, p 204).

2.3.4 Energy prices

Future energy prices will determine how the energy system and the society will develop in terms of energy production, distribution capacity and changes in energy demand caused by energy efficiency improvements. Energy prices are mainly determined based on the short-term supply/demand balance and not by scarcity of future energy resources.

> The amounts of oil above ground ready for use have much more influence on price than the amounts lying beneath the ground as future resources. The market is blind to the long term and pays no attention to ultimate sources and sinks, until they are nearly exhausted and it is too late for attractive solutions (Meadows, Randers et al. 2005, p 228).

In a perfectly competitive market, the price of energy would be determined by demand and supply which would determine the equilibrium price. Conventional neoclassical economic theory assumes that natural resources are infinitely plentiful and the market value reflects the supply and demand balance, which leads to undervaluation of exhaustible natural resources such as fossil energy (Cohen and Winn 2005). Kaufmann et al. (2008) found that the stocks of crude oil have a large influence on crude oil prices while refining capacity does not impact the prices very much. During the last few years, the increase in storage capacity has been considerably slower than the increase in demand, leading to oil price increases (Kaufmann, Dees et al. 2008).

Modelling global energy prices is difficult due to the numerous unknowns involved and the complexity of their interrelations. Regional modelling is difficult because it is misleading to isolate a single regional economy from the global economy. Belhaj and Lay (2008) found that oil prices historically have been excluded from the normal supply/demand balance and masked by different geopolitical factors. Belhaj and Lay (2008) expect an increase in oil price of approximately 6 % per year for the next two decades, until it peaks at \$ 150–180 per bbl in 2025. However, growth in China and India, combined with government energy subsidies, might cause further increase in the oil prices. This may lead to the development of alternatives to fossil fuels, which could bring the oil prices back to normal levels (Belhaj and Lay 2008). IEA's 2004 reference scenario assumed that the oil price would fall back to \$ 22 per barrel in 2006, and then climb steadily to \$ 29 per barrel in 2030 (IEA 2004). In IEA's World Energy Outlook 2007, it assumes that the world energy resources are sufficient to meet the projected demand growth to 2030 (1.8 % per year), and that the oil price will fall back to around \$ 60 per barrel by 2015 and stabilise there (IEA 2007). IEA's World Energy Outlook 2008 expects that the oil price will increase towards \$ 122 per barrel in 2030 (IEA 2008b, p 68-69). This trend indicates first of all that the price mechanisms are poorly understood and secondly that the world approach a supply restricted oil market.

The price in a market can be modelled as a simple function of demand and supply. If demand is higher than supply then prices should increase, and if demand is lower than supply then prices should decrease. Equilibrium price can then be modelled by using the equation (Sterman 2000, p 539-541):

$$P_{equil} = P_e \left(\frac{E_D}{E_S} \right)^s$$

P_e is the current price of energy, P_{equil} is the equilibrium price of energy and S is the elasticity of price to energy demand/supply balance. Energy demand and supply will be calculated based on the physical energy requirement and the physical capacity through the energy value chain. Energy demand will then be controlled by the relationship between marginal productivity of energy to energy price, and energy supply by marginal return on energy capital to capital cost.

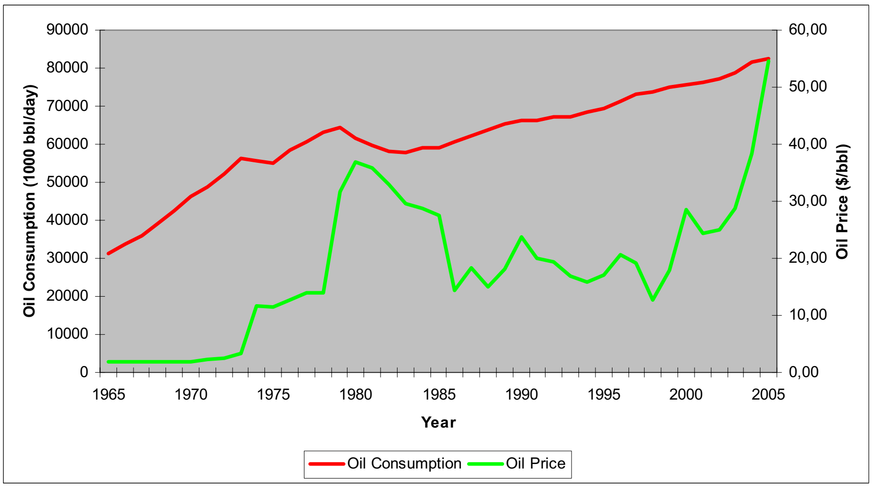


Figure 11: Historic world oil price and oil consumption.

Figure 11 above illustrates the global oil consumption and the oil price in the period from 1965 to 2005 (BP 2007). As the figure shows, there is a clear response to increasing oil prices in the late 1970's and early 1980's, where the growth in energy demand relative to GDP growth slowed down, caused by an increased focus on energy efficiency when investing in new capital goods such as cars and factories.

2.3.5 Carbon dioxide emissions

There are several environmental issues related to energy production and use, such as local pollution and smog, carbon dioxide emissions, fresh water consumption, competition between bio-fuel and food production, transport routes, noise from wind turbines, large hydro-electric dams and so on. This work however, focuses on the carbon dioxide problem.

Before the industrial revolution, atmospheric CO_2 concentrations were stable at around 280 parts per million (ppm). CO_2 emissions, due to an increasing combustion of fossil fuels and deforestation, has increased the atmospheric concentration of CO_2 to approximately 386 ppm, of which fossil fuel combustion accounts for 75-85 % (Jaccard 2005, p 43; IPCC 2007a, p 26). According to the World Bank (2006) and IPCC (2007c), the global energy-related CO_2 emissions in the year 2000 were 23.2 billion tons, where the majority of the emissions are related to energy production (WorldBank

2006; IPCC 2007c, p 103). The total emissions of greenhouse gases measured in CO_2 equivalents in the year 2000 is estimated to be around 42 billion ton, where energy-related CO2 emissions account for approximately 60 % of the greenhouse gases as illustrated in figure 12 below (Jaccard 2005, p 50; Stern 2007, p 196; IPCC 2007c, p 103). These non-energy greenhouse gas emissions are mainly from methane gas related to agriculture and changes in land use (IPCC 2007c, p 103).

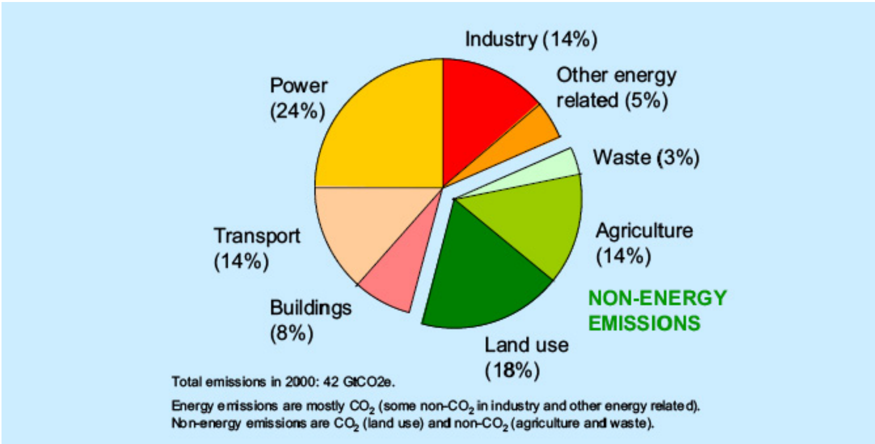


Figure 12: Global GHG Emissions in 2000, by source (Stern 2007, p 196).

Stern (2007, p 194) found that the profitable fossil-fuel resources are probably sufficient to increase the CO_2 concentrations well beyond 750 ppm, with the risk of dangerous climate-change impacts. To avoid severe climate changes while relying on fossil fuels, almost all carbon from fossil fuel use must be captured and stored, requiring permanent storage capacity for over 6000 billion tonnes of carbon (Jaccard 2005, p 197).

> CO_2 capture and sequestration (CCS) is the critical enabling technology that would reduce CO_2 emissions significantly while also allowing coal to meet the world's pressing energy needs (Ansolabehere, Beer et al. 2007).

The current level of CO_2 emissions is constrained by the efficiency and type of the existing stock of capital or equipment, with a low short-run price elasticity of demand (Newell, Jaffe et al. 2006). As an example of this challenge, two-thirds of the coal-fired power plants are more than 20 years old with average energy efficiency below 29 %

and they emit more than 3.9 billion ton of CO_2 per year. If all these coal-fired power plants were replaced by modern plants with new technology and an efficiency of 45 %, they would emit 36 % less CO_2 (IEA 2006a, p 188).

CO_2 emissions are strongly dependent on energy consumption, which again is dependent on economic growth. Figure 13 illustrates the relationship between CO_2 emissions per capita and GDP per capita in the USA.

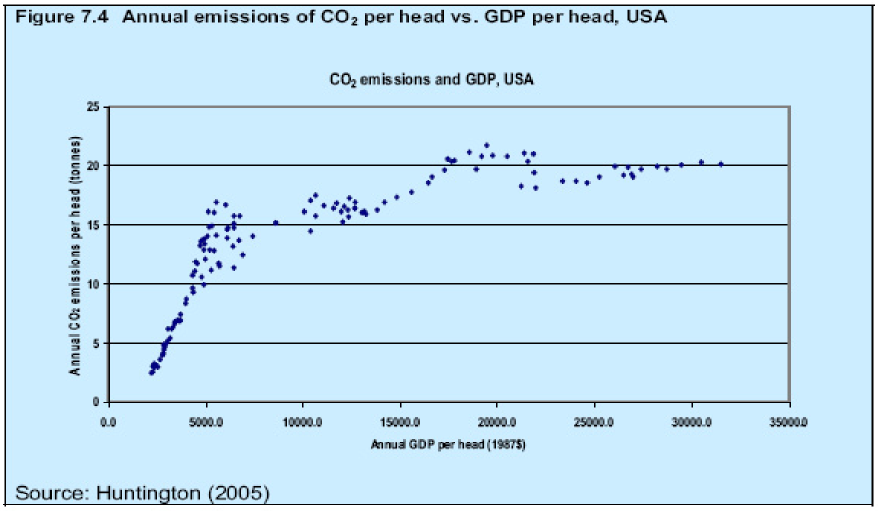


Figure 13: Annual emissions of CO2 per capita vs. GDP, USA (Stern 2007, p 207).

The CO_2 emissions per capita in Norway were approximately half of the emissions in the USA in the year 2000, with approximately the same level of GDP (WorldBank 2006). The main reason seems to be the large fraction of hydro power in Norwegian electricity production, compared with the large fraction of coal in the US combined with higher energy efficiency in the Norwegian transport sector. This demonstrates that significant reductions in world energy consumption and CO_2 emissions can be achieved without welfare loss by utilizing existing technologies.

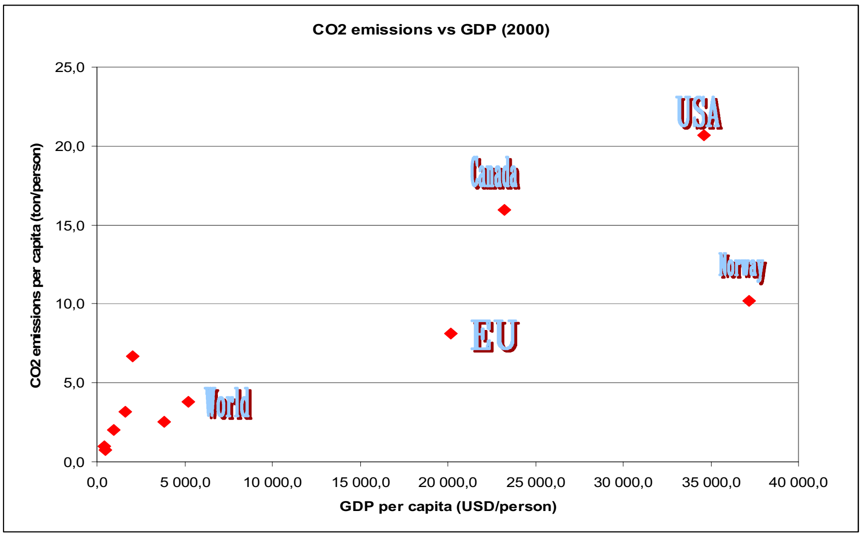


Figure 14: Carbon dioxide emissions per capita and GDP in year 2000 (WorldBank 2006).

2.4 Climate change

Climate change is important because it will limit economic growth and welfare development in different regions of the world and impose significant changes to the energy system through climate policies. Without climate change and climate policies, the world would probably turn to coal for energy security rather than renewable energy and CCS.

Climate change may have a significant impact on the future of the human population. Scientists are quite confident that human activities cause global warming and climate change, but there is still substantial uncertainty with respect to the size and consequence of global warming (Houghton 2004; IPCC 2007a, p 1-17).

The greenhouse gases were first discovered in 1896 by a Swedish chemist, Svante Arrhenius, who estimated that doubling the concentration of carbon dioxide would increase the global average temperature by 5°C–6°C (Houghton 2004, p 17). To many people, a temperature change of 2–5°C does not seem to be significant. It is a small change compared with the seasonal cycle of temperature change. The main impacts of future climate change will not be the temperature change, but significant changes in rainfall (Archer 2007, p 150).

Ice-core measurements show that there have been significant temperature variations on Earth in the last 650000 years and that the carbon dioxide levels in the atmosphere have a strong correlation to global temperature. Current atmospheric concentrations of carbon dioxide and methane are higher than they have been for the last 650000 years (Meadows, Randers et al. 2005, p 119; Siegenthaler, Thomas F et al. 2005).

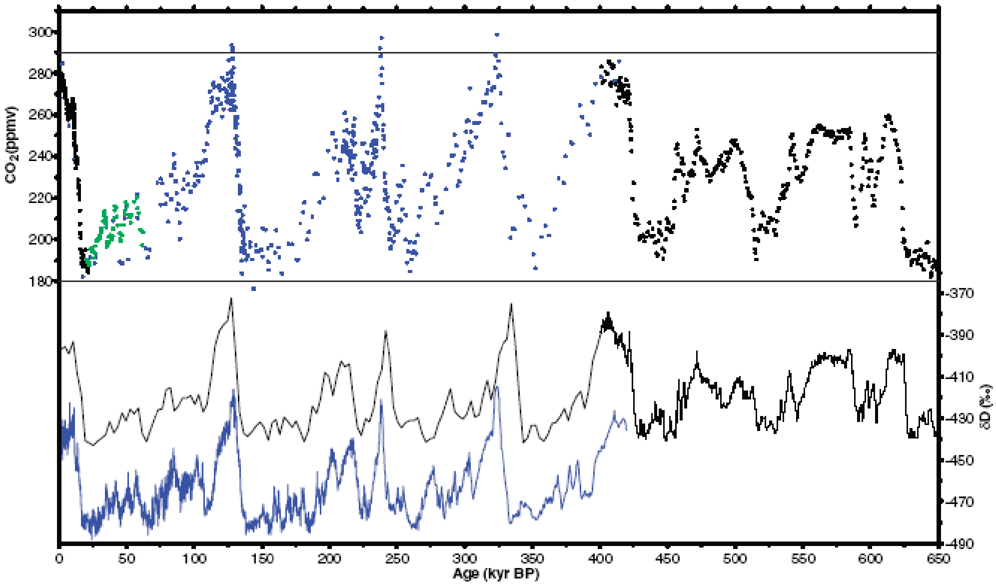


Figure 3: A composite CO_2 record over six and a half ice age cycles, back to 650,000 years before present (Siegenthaler, Thomas F et al. 2005).

In the last 65 million years, the Earth's climate system has changed from relatively high temperatures with ice free poles to a colder climate with massive continental ice-sheets and polar ice caps (Pearson and Palmer 2000). The primary force that drive this long-term climate change is the Earth's orbital geometry which affects the distribution and amount of incoming solar energy (Zachos, Pagani et al. 2001). The relationship between changes in the Northern Hemisphere summer insolation (NHSI) on orbital timescales and temperature data based on $\delta^{18}O$ data sampled from stalagmites in the Sanbao cave in China demonstrates a clear correlation between insolation and temperature for the past 224000 years (Wang 2008). In figure 16 below, these data are compared with data from the Vostok ice core.

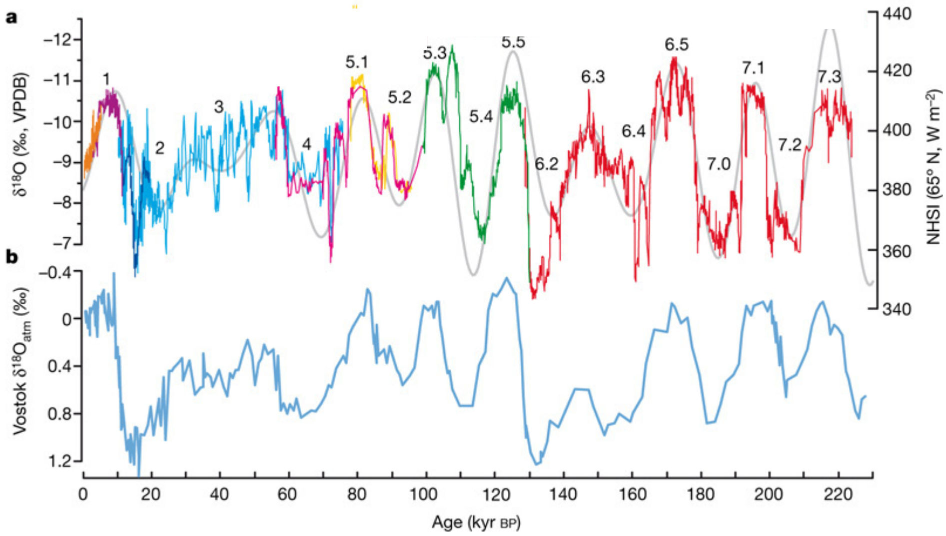


Figure16: Relationship between temperature and solar insolation (Wang 2008).

The European Project for Ice Coring in Antarctica found that there is a lag of atmospheric CO_2 concentration of 1900 years after temperature change (Siegenthaler, Thomas F et al. 2005). This indicates that the historic CO_2 concentration in the atmosphere to a large degree is a consequence of a shift in equilibrium between atmosphere and ocean caused by changes in ocean temperature due to changes in solar insolation.

Changes in greenhouse gas concentrations increase the atmospheric absorption of outgoing radiation and can therefore cause climate change on Earth. IPCC (2007a) estimates the temperature increase in the atmosphere since 1850 to be approximately 0.76°C. The oceans have also warmed during the last 50 years, accounting for more than 80 % of the changes in the energy content of the Earth's climate system (IPCC 2007a, p 37, 47).

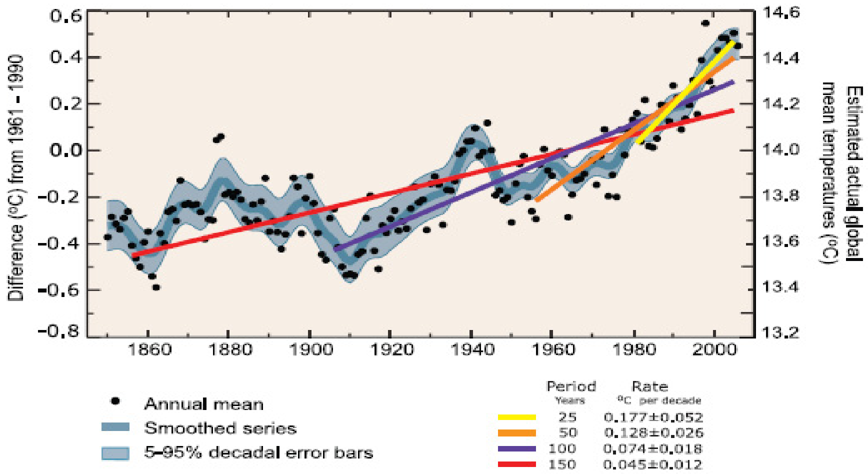


Figure 17: Global mean temperature increase since 1850 (IPCC 2007a).

Based on models and observations, IPCC (2007a) found that the equilibrium climate sensitivity, the equilibrium temperature change at a doubling of CO_2 concentration, is *likely* to be between 1.9°C and 4.4°C with a best estimate of about 2.9°C. However, IPCC (2007a) found that there is a possibility of climate sensitivity above 6°C. The largest uncertainty in the estimates is related to cloud feedbacks (IPCC 2007a, p 65-66). A 3°C increase from pre-industrial temperature would eliminate most of the Greenland Ice Sheet, causing a sea level rise of approximately 7 metres, while the Antarctic Ice Sheet probably will remain too cold for widespread melting (IPCC 2007a, p 80). Figure 18 below gives an estimate of temperature change caused by changes in CO_2 concentration, and has been used in the rest of this thesis (IPCC 2007a, p 66).

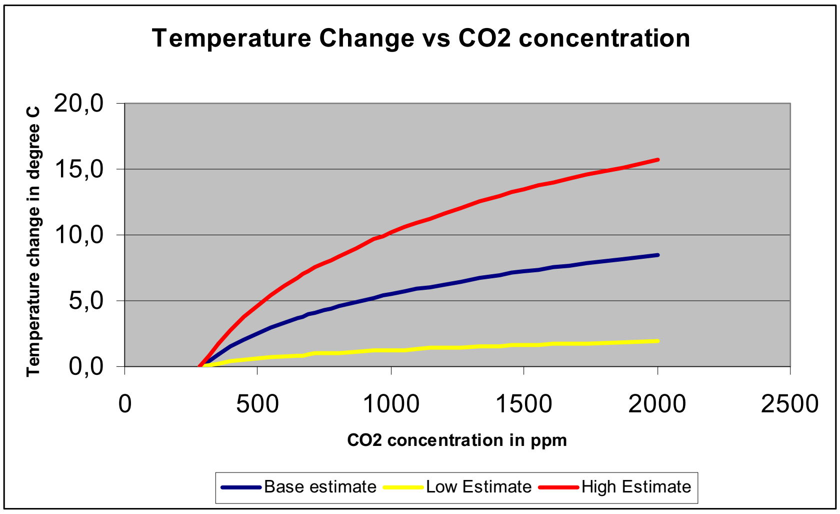


Figure 18: Expected temperature change at equilibrium from pre-industrial level based on IPCC.

The atmospheric concentration of carbon dioxide is dependent on the carbon dioxide emissions and the carbon flux from atmosphere to the biosphere, oceans and carbonate deposits. The oceans contain approximately 50 times more carbon than the atmosphere and are probably responsible for the large changes in atmospheric CO_2 over the glacial cycles. On geological timescales of millions of years, geological processes contribute to stabilise atmospheric CO_2 and the climate of the Earth (Archer 2007, p 96). The major sink for anthropogenic CO_2 over the past 200 years has been the ocean, which has contributed to reduce the atmospheric CO_2 concentration by about 55 ppm. The ocean uptake has so far removed approximately 35 % of the historic anthropogenic CO_2 emissions. However, the ocean's uptake might slow down as the ocean temperature increases (Sabine, Feely et al. 2004).

Increasing atmosphere temperature increases the temperature of the ocean surface, which decreases the solubility of CO_2 in water. This results in degassing of CO_2 to the atmosphere. This will work as a positive feedback mechanism, accelerating the CO_2 concentration and temperature increase in the atmosphere. As the temperature increases the biosphere will increase uptake of CO_2. This negative feedback loop should contribute to stabilise carbon dioxide concentration in the atmosphere (Archer 2007, p 88-94). The strength and balance of these two mechanisms will be the major factors deciding how nature will handle carbon dioxide emissions.

Cox et al. (2000) found that the terrestrial biosphere will act as an overall carbon sink until about 2050 in a "business as usual" scenario, but it will turn into a source thereafter, and by 2100, the ocean uptake rate will be balanced by the terrestrial carbon source. This will result in higher atmospheric CO_2 concentrations and higher temperatures than current IPCC estimates (Cox, Betts et al. 2000). Due to ocean temperature increases, it is likely that the ocean uptake will also slow down and contributes to an even greater increase in CO_2 concentrations.

2.5 Economic impact of climate change

Climate change is usually modelled as a reduction in productivity (Fiddaman 1997; Nordhaus and Boyer 2000). In this thesis, an approach where climate change increases depreciation has been used as described in section 2.2.2.

The economic system can be explained by a few feedback loops. Capital accumulation, population and productivity growth drive economic growth. Capital requires energy input to be efficient, which creates carbon emissions. Carbon emissions increase CO_2 concentration and cause temperature increase and climate change. Damage is created by changes in climate, which increase the depreciation rate of capital and slow economic growth (Fiddaman 2002). The impact of climate change will vary between different regions. Nordhaus et al. (2000) found that:

> Russia and other high income countries are likely to benefit slightly from a modest global warming. At the other extreme, low-income regions – particularly Africa and India – and Western Europe appear to be quite vulnerable to climate change. The United States appears to be relatively less vulnerable to climate change than many countries (Nordhaus and Boyer 2000, p 14).

Nordhaus and Boyer (2000) estimated the cost of catastrophic impacts such as increased frequency of storms and flooding to be approximately 1 % of GDP at 2.5°C warming and 7 % at 6°C warming. The impact is expected to be approximately twice the average in Europe and India. Europe is vulnerable due to the potential shifts in ocean currents and significant costal and agricultural impacts. India is vulnerable to climate changes because of the potential shifts in the water cycle. Russia is expected to experience losses on the global average, while the remainder of the world is expected to have losses around half of global average (Nordhaus and Boyer 2000, p 90-98).

Based on IPCC (2007b) it is reasonable to assume limited impact on the global agricultural output up to 3°C warming, and an exponential decline in productivity of 2 % per 1°C for temperature increases above 3°C, doubling for each degree. However, total agricultural output is expected to continue to increase due to improvements in agricultural efficiency for the next 30–50 years (IPCC 2007b, p 300). In total, global food production per capita is expected to remain constant for a global warming of up to 3°C, but with large regional differences.

Nordhaus and Boyer (2000) found that a warming of 2.5°C would cause damage of about 2 % of GDP while a warming of 6°C would cause damage costs of 10 % of GDP. They estimated the cost of future climate damages to around $4 trillion in present value (Nordhaus and Boyer 2000, p 95 and 129). The Stern Review (2007) found that the cost of climate change could be at least 5 % of GDP, maybe as much as 20 %. Stern (2007) estimated the cost of climate change at 0–3 % of GDP at a warming of 2–3°C, and 5–10 % of GDP at a warming of 5–6°C (Stern 2007, p 161).

A reasonable assumption would be to base expected global and regional climate cost on Nordhaus et. al. (2000, p 90-91), which is supported by Stern (2007) and IPCC (2007b). Based on Nordhaus and Boyer (2000), the following aggregated cost of climate change has been used:

Region	Damage at 3°C warming (Cost in % of GDP)	Damage at 6°C warming (Cost in % of GDP)
Norway	1	5
Europe	4	17
North America	1	5
Asia Pacific	2	10
Rest of the World	3	11

Table 5: Aggregated economic impact of climate change

The damages used in the modelling are estimated to have a variance of +/- 50 %, with a normal distribution. Stern (2007) concluded that: "We badly underestimated the degree of damages and the risks of climate change", and argues that governments and business should invest between 1 and 2 % of global GDP annually in new technologies and efficiency measures to avoid climate change of catastrophic proportions. In Stern's view:

> We need to have zero carbon electricity, or very close to it, by 2050. That means carbon capture and sequestration (CCS) in electricity by 2050, it means nuclear, it means renewables (Stern, quoted in Fortson 2008).

Due to the long time between cause and result, climate changes will come rather slowly, which makes it possible for the industrialised world to adapt to the changes with sensible policies to minimise the economic impact. Meeting the energy needs of a growing world in an environmentally sound fashion will require substantial investment and continuing technological innovation (Esser 2005). This will require that consumers will have to be willing to pay the full cost of energy – including the environmental costs – to make these technologies competitive (IEA 2004, p 31).

2.6 Innovations and technological change

In the entrepreneurial process, human, technical and financial resources are used to find new ways of satisfying needs. This is an uncertain process which requires experimentation with alternative approaches that may prove technically and economically unsuccessful (Ergas 1987). Entrepreneurship and entrepreneurial activity require; the existence of opportunities, the ability to recognise information about opportunities, a decision to act upon an opportunity, the ability to bear risks, organisation and innovation (Shane 2003, p 6-8). The role of the entrepreneur is to break traditional patterns to maximise value creation requiring more experimenting and risk taking than are needed in a more traditional role (Landström 2005, p 90).

Entrepreneurial theories have two main directions; Schumpeterian opportunities, which result from disequilibrating forces, and Kirznerian opportunities, which are the result of equilibrating forces, where the entrepreneur utilises existing disequilibrium in the system to bring the economy closer to equilibrium. Kirznerian opportunities reinforce established ways of doing things, whereas Shumpeterian opportunities disrupt the existing system (Shane 2003, p 20; Landström 2005, p 48). Kirznerian opportunities can be described as a process of continuous improvement to close market gaps by reducing costs and improving the existing product to satisfy customer's needs. Schumpeterian opportunities are more disruptive in its character, where they create or open up the market for new products and concepts that did not existed to the customers before. Shane (2003) defines an entrepreneurial opportunity as:

> A situation in which a person can create a new means-end framework for recombining resources that the entrepreneur believes will yield a profit (…) rather than just optimising within an old framework (Shane 2003, p 18).

There are three categories of Schumpeterian opportunities, which introduce changes that create potential for entrepreneurial profit (Shane 2003, p 23). These are:

- Technological changes
- Political and regulatory changes
- Social and demographic changes.

Technological changes are the most important source of entrepreneurial opportunity because these changes make it possible for people to allocate resources in more productive ways (Shane 2003, p 24). Political decisions can facilitate entrepreneurship through changes in how society is organised. This can be through deregulation or other institutional changes (Davidsson 2004, p 11). There is currently a lot of focus on how policies and regulatory changes can contribute to the development of renewable energy, through instruments such as subsidies, green certificates and feed-in tariffs. The understanding of technology progress and learning curves is essential in developing strategies for renewable energy technologies. Learning effects and economies of scale are of major importance for technology policies because new technological innovations often require public support at the early stages of their development. The learning curve represents the technological progress associated with a technology due to improvements by R&D, experimentation and implementation throughout the production process, directed by social and economic policies as well as economic opportunities (Isoard and

Soria 2001). Technology learning rates between 5 % and 35 % have been experienced in the energy industry (Neuhoff 2008), which is consistent with theories of learning and economies of scale, as illustrated in figure 19 below (Stern 2007, p 254).

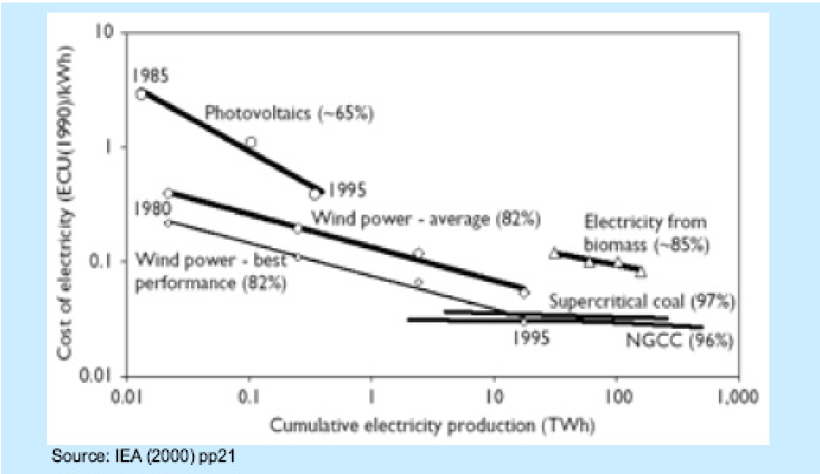


Figure 19: Cost evolution and learning rates for selected technologies (Stern 2007, p 254).

For opportunities that require economies of scale or large amounts of capital, innovation by large firms is favoured because the opportunity is difficult to exploit on a scale that most new firms can achieve with the resources that they possess (Shane 2003, p 123). Offshore wind power and CCS is an opportunity for Norway to create a disruptive change.

> Leadership in sustaining innovations – where information is known and plans can be made – is not competitively important. In such cases, technology followers do about as well as technology leaders. It is in disruptive innovations, where we know least about the market, that there are such strong first-mover advantages. This is the innovator's dilemma (Christensen 1997, p xxii).

The strategies for confronting disruptive technological change should be plans for learning and discovery rather than plans for execution because markets that do not exist cannot be analysed (Christensen 1997, p 143). Several authors have described the established firm's inability to pursue new entrepreneurial opportunities. Utterback

(1996) found that getting off the current path when discontinuities surface and identifying a path to the future is difficult:

> Only the prospective and imminent loss of the established business can justify a shift by a major firm, but this often seems impossible or incredible to them, even when it is clearly beginning (Utterback 1996, p 231).

Porter (1990) found that change is unnatural in successful companies, because powerful forces are at work to avoid and defeat it. However, creating sustainable advantages often means that a company must make its existing advantage obsolete. Established firms will usually not invest in opportunities that cannibalise their existing operations, which creates strong incentives against pursuing opportunities that are based on radical innovations (Shane 2003, p 226). A bureaucratic organisational structure as often are found in large organisations will increase the likelihood of a spin-off because the exploitation of uncertain entrepreneurial opportunities requires an organisational flexibility that is not present in such organisations (Shane 2003, p 228). Perez (2003) found that established firms will invest to improve solutions to their own products and processes when they face paradigm constrictions which could involve minor uses of radical new technologies. As the low-risk investment opportunities in established paradigms begin to diminish, there is a growing mass of capital looking for profitable uses that is willing to venture in new directions. Financial capital is mobile, while production capital is tied to concrete products, and works as an enabler of a massive shift in investment required by technological shifts (Perez 2003, p 71-73).

Energy technologies will need to make significant advances to stabilise atmospheric CO_2 concentrations at acceptable levels. The reference case by IPCC (2007b) assumes that the majority of these technological innovations will come about without a policy that focuses on creating the conditions for such innovations to occur (Pielke, Wigley et al. 2008). Technological innovations are unlikely to happen by themselves, however. A shift towards a sustainable path will require significant governmental support to overcome the initial barriers related to costs and barriers to entry.

2.7 The political landscape

The political landscape will determine the ability of the nations to solve the challenges of energy and climate. It will also have implications on the ability of nations to develop competitive advantages within the energy sector. This section will discuss present policies within different areas and the implications of these policies.

2.7.1 Economic policy

Economic growth is necessary to end poverty. In the current economic system growth takes place in the already rich countries and continues to widen the gap between rich and poor. From 1960 to 1995, the richest 20 % have increased their income compared to the poorest 20 % by approximately a factor of three. In poor countries, industrial capital per capita hardly grows because immediate requirements leave little output for industrial investment (Meadows, Randers et al. 2005, p 41-45). Developing countries are unlikely to see their incomes and living standards increase without improved access to modern energy services (IEA 2004, p 30).

> We define growth as an increase in throughput, which is the flow of natural resources from the environment, through the economy, and back to the environment as waste. It is a quantitative increase in the physical dimension of the economy and/or of the waste stream produced by the economy. This kind of growth, of course, cannot continue indefinitely, as the Earth and its resources are finite. While growth must end, this in no way implies an end to development, which we define as qualitative change, realization of potential, evolution towards an improved, but not larger structure or system – an increase in the quality of goods and services provided by a given throughput. The idea of "sustainable development" (…) is development without growth – that is, qualitative improvement in the ability to satisfy wants (needs and desires) without a quantitative increase in throughput beyond environmental carrying capacity. Carrying capacity is the population of humans that can be sustained by a given ecosystem at a given level of consumption, with a given technology. Limits to growth do not necessarily imply limits to development (Daly and Farley 2004, p 6).

Ayres (1996) argues that it is theoretically possible to have economic growth in the sense of providing better and more valuable services to consumers without necessarily consuming more physical resources. Daly (1996) argues that sustainability as a concept is not incorporated into economic theory because the economics of the past 50 years has been focused on economic growth or growth in gross national product. Economic theory assumes that unlimited growth is possible because it assumes that there is no economic limit where the marginal costs of further growth become greater than the marginal benefits (Daly 1996, p 27). Many economists assume that there are infinite resources, through substitution. However, the implication of diminishing elasticity of substitution is that there are limits of substitution where it will be difficult to cut down on pollution or energy use based on substitution alone. The economic history shows that resource and environmental limits have not halted growth in the past and economists argue that it will not do so in the future. Daly (1996) and Reynolds (1999) argue that the only way to reduce pollution or energy use below a certain point is by cutting consumption and reducing living standard (Daly 1996, p 34; Reynolds 1999). Neoclassical economic theory is not applicable as the economy approaches its limits – the Earth's carrying capacity (Daly 1996, p 37).

> The notion that we can save the "growth forever" paradigm by dematerialising the economy, or "decoupling" it from resources, or substituting information for resources, is fantasy (Daly 1996, p 28).

Gross Domestic Product (GDP) is a measure of the total costs of a society rather than welfare (Daly 1996, p 104). GDP treats costs related to pollution the same way as costs related to sustainable food production, and does not distinguish between wealth creation and environmental costs (Daly 1996, p 40). GDP does not include changes in natural stocks and funds, such as depletion of geological stocks, or disruptions of environmental functions. Environmental pollution could increase demands for commodities and services and consequently lead to an increase in GDP (Daly 1996, p 112).

Discounting is used in economic evaluation to compare the value of a future good against the value of a good now. The social-time-preference is a parameter that puts a value on this, where the cost of deferred consumption can be modelled. If the discount factor or time-preference factor equals 2 %, then you say that if consumption per capita were the same 36 years from now as it is today, you would value the consumption of your children and grandchildren half as much as you value your own consumption now. Assuming that future generations count very little, then investments with long-run pay-offs, such as environmental protection, would not be favoured. Ramsey thought that time-preference was a human failing and argued that society, which intends to live for ever, should make the discount factor equal to zero (Solow 2000, p 83): “If you care little about future generations you will care little about climate change” (Stern 2007, p 54).

Stern (2007) concludes that the time discounting should be small because it is only relevant to account for the exogenous possibility of extinction (Stern 2007, p 60). When societies are evaluating climate-change policies, the fundamental trade-off that society faces is between consumption today and consumption in the future. Nordhaus et al. (2000) argue that to reduce emissions of greenhouse gases today, society would have to reduce the output that can be used for consumption and investments and invest in climate reduction to reduce future damages and therefore increase future consumption. However, the time periods between emissions reductions and climatic impacts are extraordinarily long and uncertain, which makes this very difficult (Nordhaus and Boyer 2000, p 9). “We see little ‘real world’ evidence that the richest people or nations ever lose interest in getting richer” (Meadows, Randers et al. 2005, p 156).

The economy cannot grow to an unlimited extent, and will have to adjust to the environmental and resource limits of the Earth. If society continues on the current path, where the rich get richer, and the poor poorer, inequality will increase both between nations and generations. Providing an acceptable welfare level for the entire population of the Earth would require a different way of thinking related to economy, environment and natural resources. Currently, the wealthy population increase their economies through the use of limited natural and environmental resources, leaving fewer resources for the rest of the population or future generations. The world is still on an economic growth policy, where most nations pursue their own national, corporate, or individual self-interests. So far humanity has failed to achieve the goals of the Rio de Janeiro climate change summit (Meadows, Randers et al. 2005, p xiii), where general principles on policies to avoid climate change and environmental degradation were established (UN 1992).

The current economic thinking is based on a drive for economic growth in all nations to increase welfare. It is unlikely that a sustainable global economy can be achieved without a shift towards an economic thinking where economy is coupled with availability of natural resources.

2.7.2 Energy policy

Analysing the data for reserves and resources presented earlier in this thesis, and assuming a continued economic growth of 2 %, it is found that the world supplies of fossil fuels will struggle to meet demand beyond 2025, as figure 20 illustrates. Unless the various economies are prepared to fill the gap through renewable energy sources or through major energy efficiency improvements, the world will experience a significant increase in energy prices.

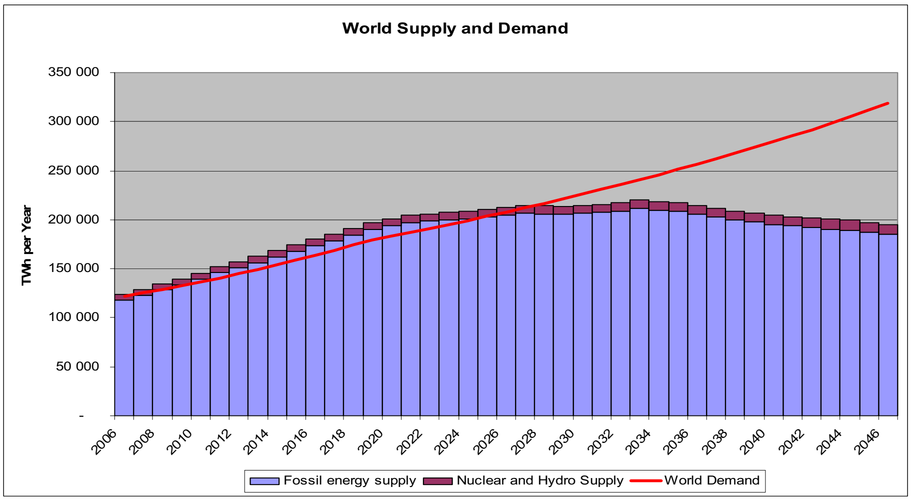


Figure 20: World primary energy supply and demand, assuming a 1.5 % yearly growth in energy demand and assuming that all reserves and resources as estimated today can be produced.

As illustrated in figure 20 there is balance between global energy supply and energy demand to approximately 2025. However, the energy security situation for Asia, Europe and North America will become increasingly more difficult after 2015. The situation will probably be worse than described in figure 20, because the high growth rate of energy exporting regions such as the Middle East, the Caspian and Russia will create increased domestic energy demand, leaving less energy resources to export to Asia, Europe and North America (Gately 2007) as illustrated in figure 21.

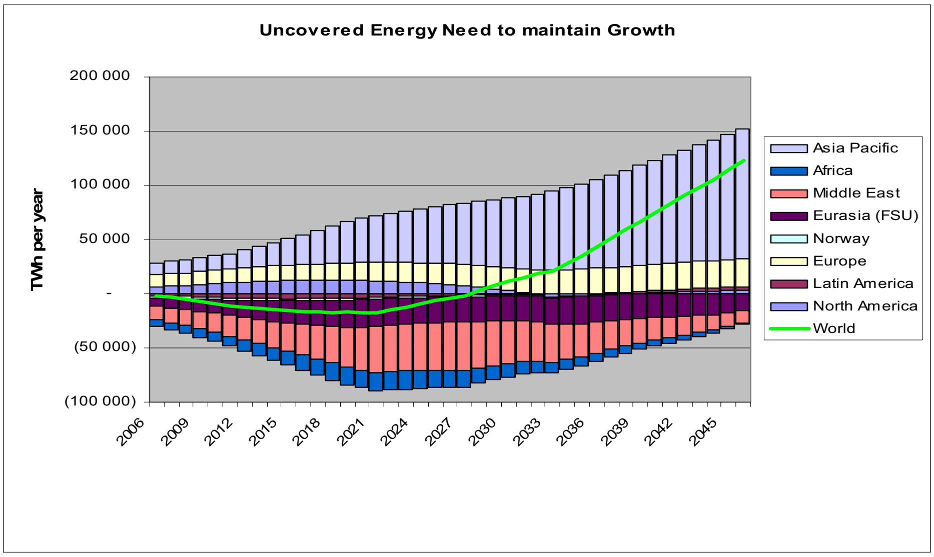


Figure 21: The figure shows the gap between energy demand and domestic energy production, where the regions above zero have a net energy import requirement, while the regions below the line have a net export capacity. The Green line shows the global supply/demand balance.

Renewable energy will bring benefits for Europe through improved energy security and reduced carbon intensity of energy production. However, renewable energy requires initial support from technological policies to achieve learning effects before they can take advantage of scale effects in production (Isoard and Soria 2001). Carbon tax or carbon trading, combined with energy efficiency regulations, might be an efficient tool to move the energy system towards renewable energy and zero-emission fossil fuels. For energy security reasons, increased domestic energy production can be achieved through increased energy prices or subsidies. Increased reliability of energy imports can be achieved by increased diversity in energy import, either through increasing the number of suppliers or increasing the number of transport routes. However, this seems to be increasingly more difficult due to increased domestic energy consumption in energy-exporting nations and increased geopolitical instability.

Hopefully we will live to see that the words of Sheikh Rashid bin Saeed Al Maktoum, who was the Prime Minister of the United Arab Emirates from 1979 to 1990 and Emir of Dubai, proved wrong: "My grandfather rode on a camel, my father rode in a car, I ride in a jet, my children will ride in cars, and my grandchildren will ride on camels" (Simmons 2008).

2.7.3 Climate policy

Climate policies will have significant influence on the development of the energy system, and the growth of renewable energy production in particular. Currently the world economy does not see sufficient investment in renewable energy resources and does not have the necessary mechanisms in place to achieve a significant reduction in carbon emissions (Deutch 2005). The Kyoto Protocol is a first agreement to start the process of reducing greenhouse-gas emissions with a target of a reduction of 5.2 % in emissions by 2008–2012 relative to 1990 in Annex I countries (Pittock 2005, p 22). Most of the countries that have signed the Kyoto Protocol are not on a path to achieve their Kyoto commitments through domestic actions. However, many of the countries, such as Norway, intend to reach their target by purchasing emission permits from other signatories or by making abatement investments (CDM) in developing countries that do not have specified targets. The Kyoto Protocol, as it is today, will not create a significant decrease in the global greenhouse-gas emissions because countries like China and India do not have abatement commitments. The main emitter, the USA, has withdrawn from the protocol (Jaccard 2005, p 182).

There are in principle two strategies towards climate change, adaptation or mitigation (IPCC 2007b; IPCC 2007c). Adaptation to environmental change is essentially to cope with the climate change and a sea-level rise that cannot be avoided now and in the near future, while mitigation would try to limit the extent of future climate change (Pittock 2005, p 133). Wealthy, developed countries in general have more capacity to adapt, because they can afford the expense of climate change (Pittock 2005, p 144). Mitigation, in contrast to adaptation, needs time to take effect due to the delays in the climate system and the time necessary to reduce emissions sufficiently to stabilise climate (Pittock 2005, p 151). The long delays in the climate system result in long intervals between when environmental policies are put in place and when the fruits of the policies become apparent. Climate changes that will occur in the next 30 years are already set in motion, while policies put in place over the next 30 years will not yield results until 30 years after that (Pittock 2005, p 54). Policies must motivate businesses and consumers to innovate and invest in zero-emission technologies at the time of capital investment while avoiding shocks to the economic system, such as dramatic increase in energy prices or loss of competitive position with unregulated trading partners (Jaccard 2005, p 270).

Implementation of CCS will add costs to coal and gas power production. A CO_2 price of approximately \$110 per ton of carbon would make coal power plants with CCS cost competitive with coal power plants without CCS. Use of CO_2 for enhanced oil recovery seems to have limited significance for large-scale CO_2 sequestration (Ansolabehere, Beer et al. 2007). CCS will increase the total demand for primary energy due to the reduced efficiency in power production. This increase in demand may have a larger impact on energy market prices than a CO_2 tax due to the low elasticity in energy demand to price, increasing the total income to energy-producing nations on a short-term basis. CCS is necessary in coal fired power plants because it is "the only major fossil fuel source where big consumer nations still have large stores within their borders" (Fortson 2008; Schleich and Gruber 2008).

Nordhaus (2007) argues that the conclusion in the Stern Review (2007), suggesting a carbon tax of around \$300 per ton to achieve a global CO_2 emission reduction of between 30 % and 70 % the next two decades, is about ten times higher than the level of carbon tax suggested by standard economic models. Nordhaus (2007) found that the difference almost entirely comes from the use of a discount rate close to zero. The use of a zero discount rate, as in the Stern Review (2007), means that all generations into the indefinite future are treated the same, whereas a positive discount rate means that the welfare of future generations is reduced or "discounted" compared with closer generations. This approach would not be consistent with current real interest rates, and would in Nordhaus (2007) opinion be too pessimistic an assumption.

The risks of climate change can be substantially reduced if the world succeeds in stabilising CO_2 concentration in the atmosphere between at 450 ppm and 550 ppm. Stabilisation of CO_2 concentration requires annual emissions 80 % below current levels (Stern 2007, p xvi). An efficient policy requires credibility, flexibility and predictability to secure investments in long-lived capital stock such as power plants (Stern 2007, p 370). International cooperation and action would require a global carbon price, created through internationally harmonised taxation or intergovernmental emissions trading (Stern 2007, p 532).

Nordhaus and Boyer (2000) argue that global climate policies should weigh the costs of slowing climate change against the benefits of slower climate change. Nordhaus and Boyer (2000) argue that the Kyoto Protocol does not have this link. The impact of the Kyoto Protocol on global temperature will be small in the next century because "the rapidly growing emissions in developing countries are uncontrolled under the Kyoto Protocol" (Nordhaus and Boyer 2000, p 69).

Gerlagh and Zwaan (2006) investigated the efficiency of different policies to achieve a stabilisation of atmospheric CO_2 concentration at 450 ppm. Gerlagh and Zwaan (2006) found that at least half of the global energy supply needs to be renewable energy by the end of the century to achieve stabilisation of atmospheric CO_2 concentration at 450 ppm. Without CCS implementation, renewable energy would have to supply 80 % of the market. To achieve this objective, Gerlagh and Zwaan (2006) found that the most efficient policy would be a portfolio standard for CO_2 emissions or a carbon tax where the tax revenues are reinvested into renewable energy production and CCS.

Global policies are gradually moving towards sustainability, although slowly, and it is interesting to note the political movement that has occurred in California:

> I believe in free trade, and I believe that it lifts everyone's standard of living. But eventually we will look at those countries that produce goods without regard to the environment the same way as we look at countries that produce goods without regard to human rights. My guess is that within the next decade or so, if an economy ignores the damages that it's doing to the environment, the civilized world will impose environmental tariffs, duties and other trade restrictions on those countries. This is a matter of fair trade. Nations cannot dump their products, and one day in the near future, they will not be allowed to dump their carbon or their greenhouse gases either. It gives them an unfair advantage.
>
> Arnold Schwarzenegger, Governor of California,
> 12 April 2007 (quoted in Nuttall and Manz 2008)

2.7.4 Innovation policies

Established firms seek to leverage on their existing business structure, focussing on the marginal cost of new investments, while new entrants are spared the dilemma of choosing between full-cost and marginal-cost options. Existing companies fail to invest in technologies that new entrants find profitable because they cannot compete against other investment opportunities on a marginal cost basis (Christensen, Kaufman et al. 2008). Established companies tend to focus on short-term earnings per share and are reluctant to invest in innovations that do not pay off on a short term basis (Christensen, Kaufman et al. 2008).

Discounting creates an anti-innovation bias as it assumes that the present health of the company or nation will persist indefinitely into the future if they do not invest in an innovation and secondly because future cash flows generated by disruptive investments are difficult to predict. Discounted cash flow is useful as long as the capabilities required for yesterday's success are adequate for tomorrow's as well (Christensen, Kaufman et al. 2008).

> More often than not, failure in innovation is rooted in not having asked an important question, rather than in having arrived at an incorrect answer (Christensen, Kaufman et al. 2008).

Stern (2007) found that a widespread shift to new or improved technology for power generation, transport and energy are needed to tackle climate change. This will require close collaboration between governments and industry to stimulate development of a broad portfolio of low-carbon technologies. Carbon pricing will, according to Stern (2007), be insufficient to reduce emissions on the scale and at the pace required. This is because the uncertainties and risks of climate change and the development and deployment of the technology are of such a scale and urgency that policies are required to support the development of low-carbon technology options. These technologies will probably be difficult to finance through the capital markets (Stern 2007, p 393).

Learning in new energy technologies is very important to develop a sustainable energy system. Carbon pricing will contribute to accelerated implementation of new energy technologies as illustrated in figure 22.

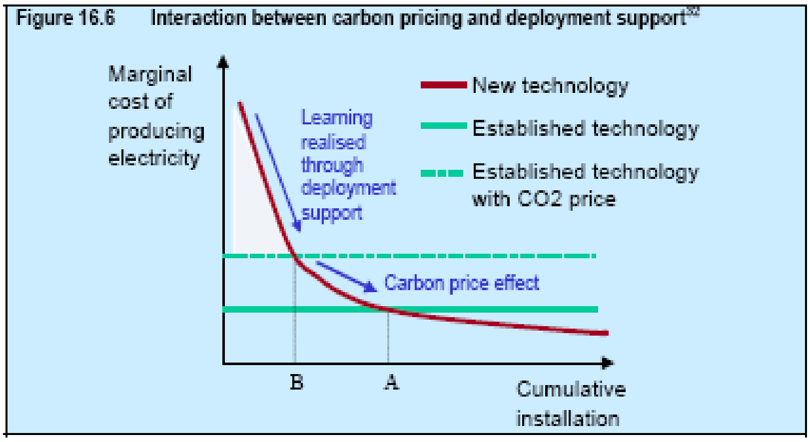


Figure 22: Carbon pricing and technology learning curves (Stern 2007).

Baumol (2003) found that technology learning after the original invention contributes far more to productivity improvement than the original breakthrough innovation. To develop efficient policies it is important to understand how the cost of new technologies develops as they approach scale economies and move down the technological learning curves. During this process, which accumulates experience through cumulative production volumes, a cost reduction of 60 to 90 % should be expected from the first pilot installations to the commercial product (Baumol 2003). In Denmark, a 70 % cost reduction on onshore wind turbines has been experienced during the first 20 years (Auken 2002).

Norwegian decision makers today find that the cost of floating offshore wind turbines is too high, relative to the expected long-term energy price, to justify an investment in the business for commercial companies (Randers, Arnstad et al. 2006, p 82-84). There are several key elements that influence the performance of an innovation system (EC 2002; Sagar and Zwaan 2006; Lund 2007; Stern 2007):

- Carbon pricing to make the polluters face the full consequence of their actions through legislative and regulatory policies

- Technology policies to bring forward low-carbon and high-efficiency technologies from the R&D base
- Removal of barriers to behavioural change to increase demand or market pull
- Instruments to overcome infrastructure barriers.

Owen (2006) found that the most efficient process of imposing the "polluter pays principle" would be to internalise as many of the externalities of power generation as possible. Estimated damage costs associated with externalities are very difficult to predict with precision, and would be a controversial policy option. Because externalities are a form of market failure, government intervention is justified in order to minimise environmental impacts on the community. This could be done by imposing an emission tax on consumption of a commodity that reflect the damage incurred by society (Owen 2006). Owen (2006) concludes that if the estimated damage costs from combustion of fossil fuels had been internalised into the price of electricity, a number of renewable technologies would have been competitive. Owen (2006) recommends removal of both direct and indirect subsidies to fossil-fuel based power generation technologies and appropriate pricing of fossil fuels to reflect the environmental damage created by their combustion as policies for stimulating the development of renewable energy technologies.

> Since innovation comes at a cost, technological solutions to the climate problem will not come about without policies in place to offer researchers incentives to pursue climate-friendly energy alternatives (Popp 2006).

To achieve success in this process it is important to work together towards common goals and shared visions, where policy incentives are combined with political stability and continuity in the process of overcoming system failures in the different stages of technology development, as described in figure 23 (Foxon, Gross et al. 2005).

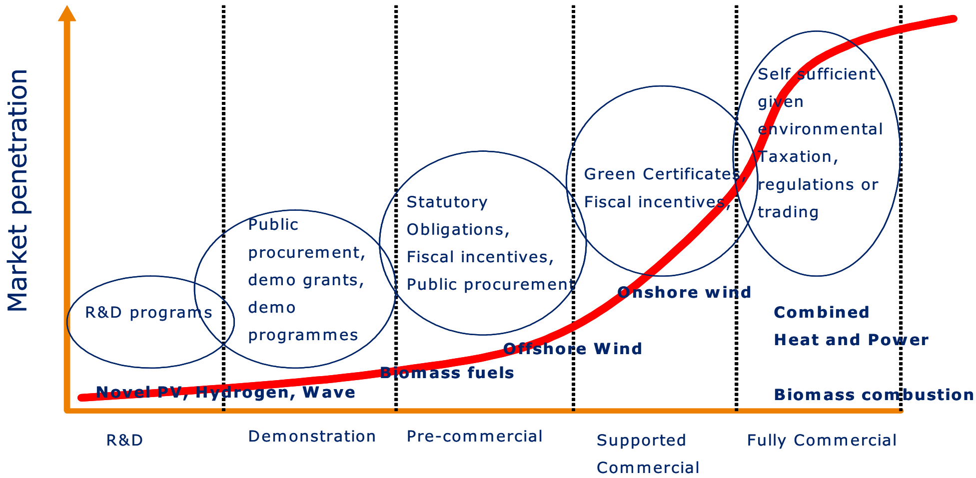


Figure 23: Technology s-curve, Technology Maturity and policy instruments, after Foxon (2005)

The need for political stability was also confirmed by Söderholm et al. (2007) who investigated the incentives for wind power in Sweden and concluded that the existing and planned policy instruments were strong enough to make wind power competitive. However, they found that the investment is strongly affected by lack of policy stability, public criticism at the local level, and the legal provisions governing the assessment of the environmental impact of wind turbines. Due to these obstacles, they conclude that a move offshore may be an efficient strategy for the development of wind turbines (Söderholm, Ek et al. 2007).

In Germany, subsidies through R&D programmes and feed-in laws was central in providing the incentives for creating growth in renewable energy together with removal of uncertainty about the future of the feed-in tariffs. Redirection of science and technology policy towards renewable energy and institutional change is also required to generate markets for the new technology, where technology-specific coalitions need to be formed and new firms must be allowed to enter the market (Jacobsson and Lauber 2006).

Auken (2002) concluded that the Danish success with wind energy is a result of a firm policy sustained over a long time period, as well as sufficient government support to overcome the extra cost of the first installations. The basis for the successful Danish wind industry is the Danish domestic market which gave it the testing ground to organise both wind technology and manufacturing technology, creating a competitive international industry (Auken 2002).

Fischer and Newell (2003) found that with an ultimate goal of reducing CO_2 emissions, policies to create incentives for fossil-fuel generators to reduce emissions intensity and for consumers to conserve energy perform much better than those that rely on incentives for renewable energy producers alone. Fischer and Newell (2003) conclude that the price of emissions is the most efficient instrument in emission reductions, since it simultaneously gives incentives for fossil-fuel energy producers to reduce emissions intensity, for consumers to conserve, and for renewable energy producers to expand production.

2.7.5 Geopolitical stability

The long-term security of energy supply to Europe and other energy-consuming nations depends on the attractiveness and accessibility of investments in the producing regions such as Russia, the Persian Gulf and Africa, as well as the capacity for transportation from these regions. These projects will only emerge if there is an adequate investment climate and geopolitical stability along the whole value chain. Geopolitical instability along these value chains will create insecurity with respect to energy supplies to Europe and enhance the value of Norwegian energy production.

> As a consequence of the geopolitical developments in the period to 2020, the probability of events affecting the security of energy supply, the exposure of the EU and the vulnerability of society to energy supply disruptions are likely to increase (Correlje and Linde 2006).

The US military invasion of Iraq and the recent Russian military intervention in Georgia can be seen as actions designed to position these nations in the energy market (NRK 2008). The US invasion of Iraq has secured access to petroleum resources in one of the most petroleum-rich countries, but probably more importantly, it has the potential of creating geopolitical stability in a future transport corridor of petroleum products. If the US is able to stabilise the region, an alternative transport route for oil from the Middle East to the Mediterranean can be established through Iraq and Turkey, reducing the risk of supply disruptions through the Hormuz strait. For Europe, this would also open up a gas import route from the Middle East, through Iraq and then through Turkey-Greece or Turkey-Ukraine. The majority of oil and gas supplies from the Caspian region today goes from Azerbaijan through Georgia-Turkey or Russia-Ukraine. It is therefore essential for the US and Europe to establish close relations with Iraq, Turkey, Georgia and Ukraine, to secure energy supplies from the Caspian and Middle East regions (Kalicki and Goldwyn 2005, p 131-146). The war in Afghanistan effectively blocks a possible gas export route from the Caspian region through Afghanistan to India and China limiting the gas leakage to the east (Victor, Jaffe et al. 2006, p 203). Russia, on the other hand, is dependent on income from oil and gas exports to increase its economic and military strength, and to regain its position as one of the superpowers in the world. Russia would like to maintain its position as the dominant gas supplier to Europe based on gas supplies from the Barents Sea and Western Siberia. Russia has a strong interest in maintaining geopolitical instability in the south, to avoid competing gas from the Caspian and Middle East entering the European market. Russia also works to establish export routes from eastern Siberia to Asia (Victor, Jaffe et al. 2006, p 337), while Kazakhstan plans to establish gas pipelines from the Caspian Sea to China and India to serve the Asian market (Kalicki and Goldwyn 2005, p 158).

USA and Europe seem to be working towards a more reliable alternative oil and gas supply from the Middle East and the Caspian while trying to block the export of these resources to Asia. Russia, on the other hand, tries to block access to gas markets for gas export from the Middle East and Caspian regions to maintain and increase the market share of Russian gas in Europe. As energy resources become scarcer, governments should expect increasing geopolitical tension based on conflicts over resources. Energy available for export will also decline as the domestic demand increases as a consequence of increasing economic welfare in the energy exporting nations.

3 Methodology

This thesis tries to quantify future energy market developments based on a qualitative assessment of future developments in climate and energy policies. This chapter summarizes the methods of investigation used in this thesis. Scenario thinking, system dynamic modelling and valuation of options are powerful tools for making strategic decisions on the governmental and business level. These tools have been combined in this work to value the potential industries of offshore wind and carbon capture and storage for Norway. The research is based on scenario analysis (Schwartz 1998), system dynamic theory and modelling (Sterman 2000), strategic management (Porter 1980) and innovation theories (Schumpeter 1934; Christensen 2004). The future European energy market have been analysed, and strategies to create Norwegian competitive advantages within renewable energy production targeted towards the European market have been investigated.

The scenarios will be used as a background to establish possible outcomes of the future. The scenario methodology is based on the “trilemma” methodology described by Rodrik (1999) and used in several scenario development processes such as “The Shell Global Scenarios to 2025” (Shell 2005). The scenario analysis will focus on three main aspects:

- Economic growth and development
- Security of energy supply
- Environmental impact of energy consumption

Energy supplies are vital for continued economic growth while the environmental impacts of energy consumption could undermine long-term economic development through severe climate changes. The scenario analysis provides the basis for evaluating different strategies for developing a sustainable energy market.

A system dynamic model has been developed and used to investigate the future European energy market, describing the main market drivers and how they influence the market dynamics. The system dynamic model will be used together with the scenario analysis to describe the future competitive landscape and establish quantitative estimates with uncertainty for the long-term development of the European energy market for the different scenarios.

Based on the scenario analysis, the strengths and weaknesses of Norway with respect to industrial development have been analysed. Incentives for developing a sustainable energy business in Norway has been investigated based on the literature on strategy and innovation (Porter 1990; Hamel and Prahalad 1994; Christensen 2004). Development of a Norwegian offshore wind power industry or an industry based on CO_2 capture and storage have been analysed. Norway has competitive advantages and competence within these areas and has the potential to become a leading industry player. Offshore wind power and CO_2 capture and storage could be developed to secure supplies of zero emission energy to Norway and Europe (Randers, Arnstad et al. 2006; ENOVA 2007).

3.1 Scenario analysis

The purpose of scenario analysis is to develop an understanding of possible outcomes for tomorrow, how the future might look like, and what to expect. In the early 1970s the oil industry was affected by a major disruption in the oil supply – the oil crisis, and consequently the Western economies entered a recession. It was a major discontinuity from the trends of the 1960s that could not be foreseen because the methods of economic analysis were not designed to look for them (May 1996, p 162). The scenario method begins from a recognition of the unpredictability of the future, but acknowledges that decisions in the present will have future implications (May 1996, p 162). Peter Schwartz (1998) is clear about the purpose and limitation of scenarios:

> Scenarios are stories about the way the world might turn out tomorrow, stories that can help us recognize and adapt to changing aspects of our present environment (…) Scenarios are not predictions. It is simply not possible to predict the future with certainty (Schwartz 1998, p 3-6).

Decision makers, such as politicians and corporate managers, are always making decisions that shape the future and these decisions are made based on expectations or forecasts of how the world will develop. Scenarios should be developed to challenge the illusion of certainty to improve the understanding of risks and realities. Scenarios cannot give an accurate picture of the future, but can help decision makers to make better decisions about the future (Schwartz 1998, p 6-9; Jaccard 2005, p 26).

There are numerous techniques and methods for developing future thinking, ranging from extrapolation through scenarios and Delphi methodology to politics (May 1996, p 112). Most methods are based on gathering of information and opinions from different sources and putting this together in a consistent way. One of several methods used to develop scenarios for the future is that developed by Polak (1973), which examines optimism and pessimism by differentiating between essence optimism/pessimism and influence optimism/pessimism. The first point of view sees history as a book that has already been written; the second sees history as a process that humans can or cannot manipulate (May 1996, p 44).

A scenario effort should begin by looking inward, examining your own mind-set, and how this mind-set influences your judgements about the future. This will open up some barriers, and help see the right questions to ask about a decision (Schwartz 1998, p 50).

The perspectives of the majority of the world's people are concerned with matters that affect only family or friends over a short period of time. Very few people have a global perspective that extends far into the future (May 1996, p 7). This follows the pattern of Maslow's (1952) hierarchy of human needs, which holds that once basic survival and security needs are satisfied it becomes possible for the individual to develop socially and personally. Thinking longer term is part of this (May 1996, p 8). Planning is a process of human forethought and action based upon that thought. It is and must be future oriented and the trick is to see the future before it arrives (May 1996, p 31).

Modern Western societies are often criticised because they have no vision; no clear idea of where they want to go or what kind of society they want to become. As Polak (1973) has argued, societies without vision inevitably decline, because they lose momentum. Visions, dreams, images of a desirable future are the necessary driving forces that urge people to change the situation (May 1996, p 88). Building scenarios starts by looking for driving forces, the forces that influence the outcome of events. Driving forces are the elements that determine the outcome of the scenario, and help you decide which factors will be significant and which factors will not. When the driving forces are identified, you must uncover the "predetermined elements" and the "critical uncertainties" (Schwartz 1998, p 101-108). Scenarios explore two or three alternatives, based on the possible behaviour of the driving forces. People cannot cope with more than two or three alternative scenarios, and two scenarios may not capture reality, so three scenarios are often enough. At least one alternative scenario should frighten the decision makers enough to think – but not so much that they shut down (Schwartz 1998, p 135-140).

> The more complex and large a business, the more complex and large the scope of the scenarios. Thus, scenarios have to be simple, dramatic, and bold – to cut through the complexity and aim directly at the heart of an individual decision (Schwartz 1998, p 193).

Another methodology for developing scenarios is based on the political trilemma of the world economy, as Rodrik (1999) describes it, arguing that international economic integration, the nation-state, and mass politics cannot co-exist in the long term perspective. The world has to pick two out of three objectives (Rodrik 1999). The standard trilemma is based on the identification of three main objectives of the society with associated driving forces – where the hypothesis is that the world in the long run can achieve at most two of these three objectives. Rodrik developed his trilemma by claiming that if the world wants true international economic integration, governments would have to go either with the nation-state, in which case the domain of national politics will have to be significantly restricted, or else with mass politics, in which case society will have to give up the nation-state in favour of global federalism (Rodrik 1999). The corners of the trilemma triangle are each of the different objectives with its main driving forces, where the scenarios are developed along the sides of the triangle. The basis for the method is a philosophy based on the assumption that "two wins – one loses" (Shell 2005). Shell's global scenarios to 2025 have used Rodrik's (1999) methodology to explore the three forces of market incentives, communities, and social coercion or regulation by the state. The three forces drive towards different objectives; efficiency, social cohesion and justice, and security. Shell has developed its new scenarios in the areas of the trilemma triangle that capture the most plausible trade-offs between these diverse, complex objectives, the "two wins – one loses" area at the sides of the triangle where forces combine to achieve two objectives (Shell 2005).

The scenarios in this study have been developed using the thinking behind the trilemma triangle, combined with the concepts described by Peter Schwartz (1998). This way of building scenarios could provide a balanced picture of the future development of the global energy market. Although this is just a methodology, several methods can provide a good starting point for developing scenarios. The method is not as important as the description of the scenarios.

Experiences today are the result of human actions in the past and actions today create the future for the following generations (May 1996, p 76). To believe that we can influence the future we must assume that we can influence the course of events by our actions (May 1996, p 157).

Scenario thinking and modelling by use of system dynamics can give important input on how the society may evolve, and form an important input to the external strategic analysis. However, it might be more important to create visions for the future, to create a picture of how the society should be.

3.2 Strategic analysis

> Essentially, developing a competitive strategy is developing a broad formula for how a business is going to compete, what its goal should be, and what policies will be needed to carry out those goals (Porter 1980, p xvi).

Strategic analysis and management is essentially used to understand and cope with competition. Competition goes beyond established industry rivals and should include four other competitive forces as well; customers, suppliers, potential entrants, and substitute products. The rivalry that results from all five forces defines an industry's structure and the competitive landscape within an industry (Porter 2008).

Figure 24: Porter's five forces for industry competition

If the competitive forces are intense, almost no company earns attractive returns on investment. If the forces are benign, many companies are profitable. The industry structure is the driver of competition and profitability, not whether an industry produces a product or service, is emerging or mature, high tech or low tech, regulated or unregulated. In formulation of a strategy, the strongest competitive force or forces will determine the profitability of an industry and should receive the most attention (Porter 2008).

The threat of entry in an industry depends on the height of entry barriers. If entry barriers are low, then the threat of entry is high and industry profitability is moderated. Powerful suppliers can maintain higher prices, and keep more of the value for themselves and eventually squeeze profitability out of an industry that is unable to pass on cost increases in its own prices. Powerful customers can capture more value by forcing prices down, demanding better quality or more service and generally playing industry participants off against one another at the expense of industry profitability. Buyers are powerful if they have negotiating leverage to pressure price reductions. Substitutes deliver the same functionality as an industry's product by a different means, and it is essential to identify changes in other industries that may make them attractive substitutes (Porter 2008):

> Understanding the forces that shape industry competition is the starting point for developing strategy.... Strategy can be viewed as building defences against the competitive forces or finding a position in the industry where the forces are weakest (Porter 2008).

Strategy is not just a plan to position a firm or industry in its external landscape; it also defines what a firm hopes to be. The purpose of the organisation should be at the heart of strategy and should give direction to every part of the organisation (Montgomery 2008). John Browne, the former CEO of British Petroleum, put it this way:

> A business has to have a clear purpose. If the purpose is not crystal clear, people in the business will not understand what kind of knowledge is critical and what they have to learn in order to improve performance (…) What do we mean by purpose? Our purpose is who we are and what makes us distinctive. It's what we as a company exist to achieve, and what we're willing and not willing to do to achieve it (Montgomery 2008).

Competitive advantage is essential to strategy, but it is not the ultimate goal. Strategies should identify changes inside or outside the company that either threaten its position or present new opportunity for adding value (Montgomery 2008). Industry changes bring the opportunity to spot and claim promising new strategic positions. Companies have the ability to shape industry structure and lead their industry towards new ways of competing that alter the five forces for the better. The industry participants may benefit in the process, but the innovator of the structural change can benefit most if it can shift competition in directions where it can excel. The starting point of the strategic analysis is to determine which force or forces are currently constraining industry profitability and address them (Porter 2008).

Developing a sustainable energy system into a competitive business will take several decades and will require perseverance, political leadership and financial commitment. Porter (1990) concluded that the role of the government is to encourage and push companies to raise their aspirations and move to higher levels of competitive performance. Porter (1990) found that it often takes more than a decade for an industry to create competitive advantages. Policies that would make a difference in creating competitive advantages are slow and require too much patience for politicians. According to Porter (1990) governments should follow some basic principles to create national competitiveness; encourage change, promote domestic rivalry, and stimulate innovations. National competitiveness depends on the capacity of the nation's industry to innovate and upgrade. Companies gain advantage against the world's best competitors because of pressure and challenge and will benefit from having strong domestic rivals, aggressive home-based suppliers, and demanding local customers. Nations succeed because their home environment is the most forward looking, dynamic and challenging (Porter 1990).

The presence of a network for the entrepreneur is very important in conceptualising an entrepreneurial idea. This can be through a personal network, created through personal experience, or it can be a local network in the form of a local cluster of businesses (Porter 1990). This local network requires a minimum number of businesses that are doing business within the same business segment, so the entrepreneurs can learn while competing with each other (Landström 2005, p 82).

Before a company can develop entrepreneurial opportunities into future competitive advantages it often has to unlearn much of its past. Competition for the future is competition for opportunity share rather than market share, through identification of opportunities that companies are uniquely positioned to exploit given their portfolio of competencies. Leadership in fundamentally new industries is seldom built in anything less than ten or fifteen years, suggesting that perseverance may be just as important as speed in the battle for the future (Hamel and Prahalad 1994, p 25-37). The race to the future occurs in three distinct overlapping stages (Hamel and Prahalad 1994, p 50):

- Competition for industry foresight, becoming the intellectual leader in terms of influence over the direction and shape of industry transformation
- Competition to shape the future structure of the industry to one's own advantage
- Competition for market position and market share

Creating the future is more challenging than catching up as you have to create your own road map. You must unlearn much of the past, create stretch goals that challenge the organisation to accomplish the impossible, and identify and develop the core competences required to shape the structure of future industries. To get to the future first, you have to imagine it and create it. Getting to the future first gives the opportunity to establish the rules by which other companies have to compete (Hamel and Prahalad 1994).

The broadest level of a strategy formulation involves an evaluation of the four corners in figure 25 and to determine the limits of what an organisation can accomplish (Porter 1980, p xviii).

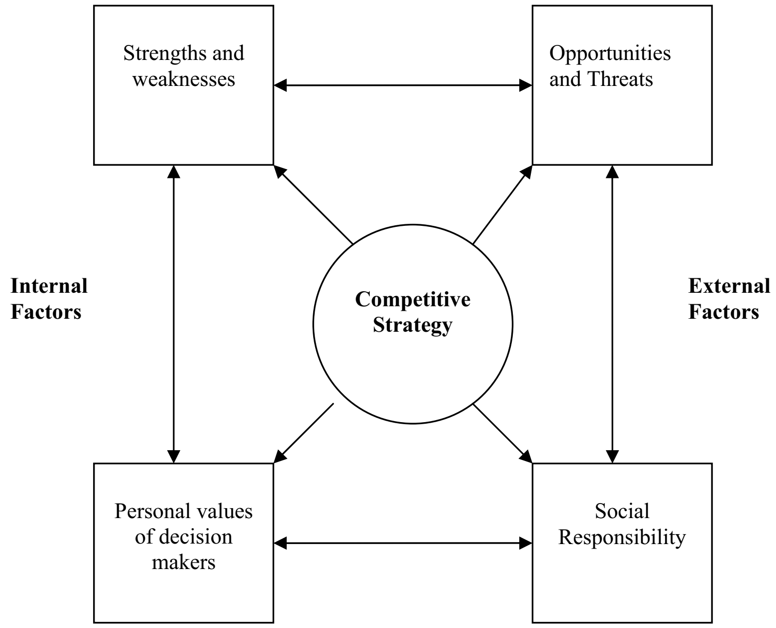


Figure 25: Context in which competitive strategy is formulated (Porter 1980).

Porter (1994) distinguishes between business unit (or competitive) strategy and corporate (or companywide) strategy. Competitive strategy concerns how to create competitive advantage in the businesses in which it competes while corporate strategy concerns two different questions: what businesses the corporation should be in and how the corporate office should manage the array of business units. Corporate strategy makes the corporate whole add up to more than the sum of its business unit parts (Porter 1994). National strategies should focus on what industries and businesses the nation should engage in on a long-term perspective.

Change is an opportunity to shape the future structure of the industry to one's own advantage, or to create competitive advantages in a new industry. The changes in energy and climate, and related policies, will probably create an opportunity within zero emission energy production. Existing strategy theories are mainly based on corporate strategies, and are not completely suitable for developing national strategies. However, there is a lot of experience from the history of industrial development in several nations, and in particular in the development of the Norwegian oil and gas industry.

3.3 System dynamic modelling

Most economic models assume a system that quickly converges to equilibrium. However, complex systems are in disequilibrium and evolve due to interactions in the dynamic system over time caused by feedback processes, nonlinearity, delays and path dependency. System dynamic thinking and modelling are tools to understand the structure and dynamics of complex systems, which is difficult to capture by use of traditional modelling tools (Sterman 2000, p vii and 21-23). The interactions between climate change, energy security and economic growth are a complex dynamic system, and system dynamic modelling is a tool that is suited to model this system. System dynamic modelling has been used in several integrated studies of global environment, economy and energy. System dynamic models have been developed for similar purposes such as World-3 which was used to investigate the relationship between sustainability and growth in "Limits to Growth" (Meadows, Randers et al. 2005), the integrated climate and economy model FREE developed by Fiddaman (1997) to study environmental and economic policies, and finally the EICOMP model which was developed to investigate how to achieve a transition towards large scale use of hydrogen (Gether 2004).

A model that tries to understand the future behaviour of social systems should be balanced. The degree of detail should be balanced between different parts of the model, with the same level of detail in all parts. Incorporating all details and distinctions into a model would not necessarily make a better model (Meadows, Randers et al. 2005, p 135-136): "A model is a simplified representation of reality. If it were a perfect replica, it would not be useful" (Meadows, Randers et al. 2005, p 130).

Complexity is underestimated by most analysts. However, even if complexity is real and an important motivation to use system dynamics, simplifying complexity is very important (Moxnes 2000). Dynamics arise from the interaction of two general types of feedback loops; positive or self-reinforcing and negative or self-correcting loops. System dynamics modelling tries to discover and represent these feedback processes, the stock and flow structures, time delays, and non-linearity's of a system (Sterman 2000, p 12). Dynamic complexity arises from the interactions in the system over time where time delays between taking a decision and its effects create instability in dynamic systems (Sterman 2000, p 21-23). Most people tend to significantly underestimate exponential growth or decline because they tend to extrapolate linearly rather than exponentially (Sterman 2000, p 29).

Learning is an important feedback process, which can be divided into a single-loop learning process, where people learn to reach goals in the context of existing mental models, and double-loop learning, where mental models of the system are reframed and changed (Argyris 1990). The limited information available must be used to align the state of the system with the goal and to revise mental models and redesign the system as illustrated in figure 26 below (Sterman 2000, p 25). Interaction between the modeling effort and the real system results in re-design and new insight about the problem. Real-life strategies, structures and decision rules make the basis for simulation models that can be used to test the virtual world of the model. The tests will in turn result in further insight and improved formal and mental models. This learning cycle is inherent in every modeling process.

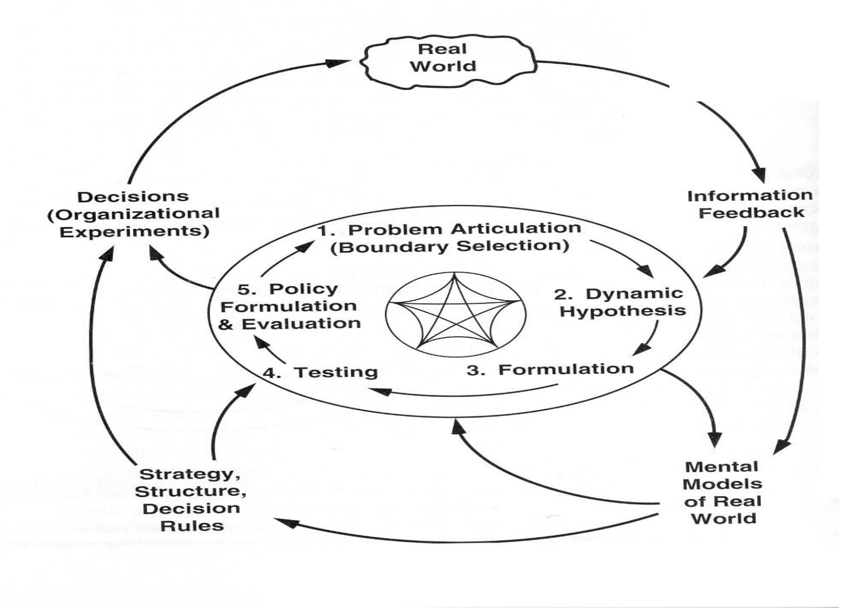


Figure 26: Effective modelling involves constant iteration between experiments and learning in the virtual world and experiments and learning in the real world (Sterman 2000, p 88).

The five principal activities in the modeling process are (Sterman 2000, p 87):

1. problem articulation
2. formulation of dynamic hypothesis
3. formulation of simulation model
4. testing
5. Policy design and evaluation.

Reality is infinitely complex. Addressing and articulating a specific problem in the system is therefore a prerequisite for a successful model, and should simplify rather than seeking an absolute representation of any social or business system. The time horizon should extend as far back as needed to capture the reason for the problem and far enough into the future to capture the delayed and indirect effects of potential policies (Sterman 2000, p 89-90).

System behavior arises from its structure. System structure is comprised of feedback loops, stocks and flows, interactions between the agents and the decision processes imposed on the system. Behavior can be broken down into fundamental modes, where complex behavior arises from the combination of these fundamental modes. The three fundamental modes are; (1) exponential growth, (2) goal seeking and (3) oscillation (Sterman 2000, p 107).

(1) Exponential growth and decline

Self-reinforcing feedback, or positive feedback, results in exponential growth, it amplifies deviations and reinforces change. For pure exponential growth, the doubling time is constant (Sterman 2000, p 108-111).

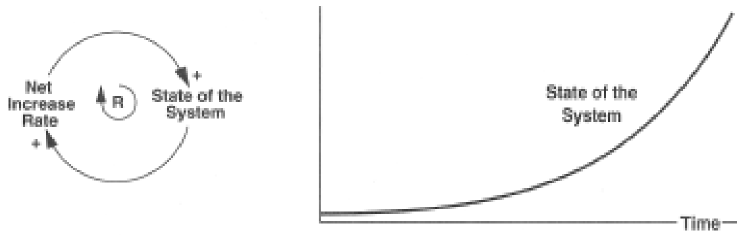


Figure 27: Exponential growth system

(2) Goal seeking

Balancing feedback, or negative feedback, seeks equilibrium. It does so by initiating corrective action that brings the system back in line with the goal every time a disturbance brings the system state away from the goal. Every negative feedback loop must therefore have a goal against which the current state of the system is compared. If the system state deviates much from the goal, the system will generate large corrective responses. Like exponential growth, goal seeking results in an exponential behavior, but in the opposite direction. If the corrective action against any gap between the goal and actual system state is proportional, then the system experiences an exponential decay (Sterman 2000, p 111-113).

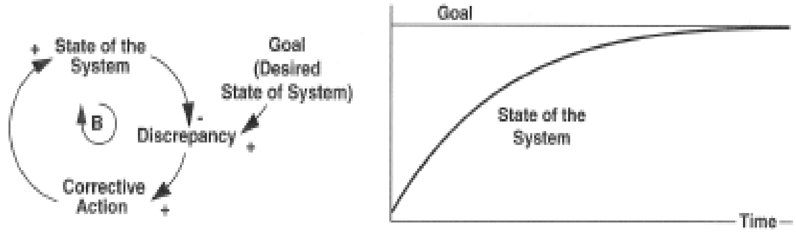


Figure 28: Goal seeking system

(3) Oscillation

If a system is dominated by a balancing feedback loop, and significant time delays exist somewhere in the loop, the system will continue to generate corrective responses even after it reaches its desired system state, creating oscillations (Sterman 2000, p 114-117).

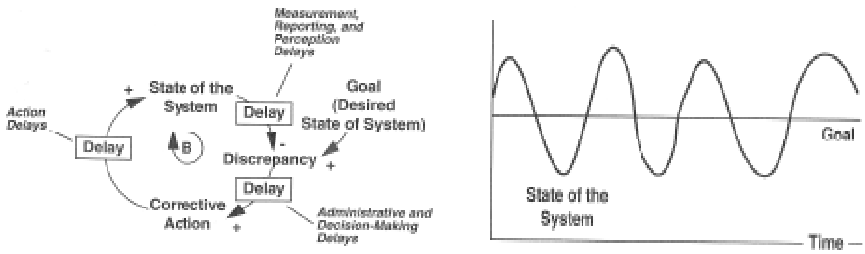


Figure 29: Oscillation in a system

The fundamental models above can interact to create other important behaviors such as; S-shaped growth, S-shaped growth with overshoot, and overshoot and collapse.

(1) S-shaped growth

No real system can sustain unlimited exponential growth and it has to decline because of constraints in the system. The behavior of such systems over time will form an s-shaped response. To generate s-shaped growth, no significant time delays can exist in the negative feedback loops and the constraints must be constant (Sterman 2000, p 118-121).

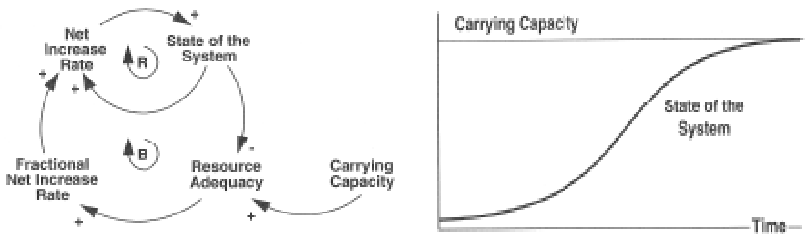


Figure 30: S-shaped growth – exponential growth combined with a goal seeking behaviour

(2) S-shaped growth with overshoot

The assumption that no significant time delays exist in the negative feedback loops does often not hold. Significant time delays results in s-shaped growth with overshoot (Sterman 2000, p 121-122).

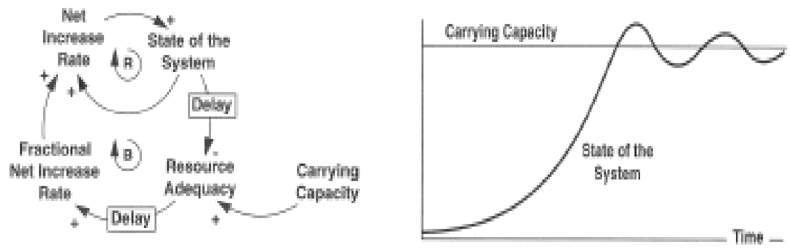


Figure 31: S-shaped growth with overshoot

(3) Overshoot and collapse

Constraints are not necessarily constant and may interact with the system. If resources are overloaded, they may collapse and the system will fold together with them. Non-renewable resources such as fossil fuel will finally be depleted and if the system is still dependent on fossil fuel it will fold (Sterman 2000, p 123-127).

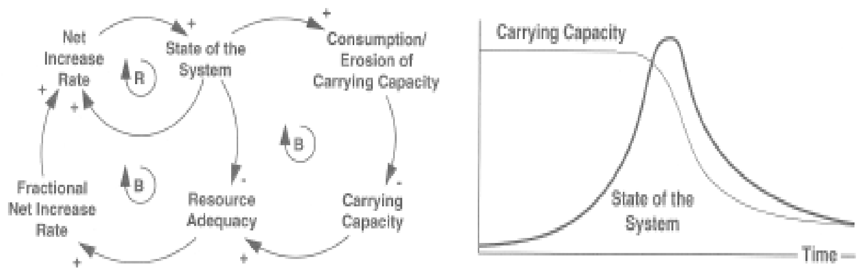


Figure 32: Overshoot and collapse

Path dependence and lock-in are important effects in the society which can be modeled by use of system dynamics. Path dependence in a system requires that positive feedback loops dominate and that the initial state is an unstable equilibrium where one or more equally attractive paths lead away from the unstable equilibrium. Depending on random shocks in the system, the path is determined and the system finds a more stable equilibrium position. Because of the self-reinforcing feedback loops, the change in the arbitrary direction is reinforced more and more. Sooner or later, the energy required to move the system to another path becomes too great and the system becomes locked in, the equilibrium is self-reinforcing (Sterman 2000, p 349-353). Although it might seem as systems that have lock-in will remain in the ultimate state for ever, the lock-in is dependent on the environment remaining constant. If the prerequisites for the lock-in are changed, the lock-in will cease to exist. For example, if the technology becomes obsolete due to a major crisis, like an economic depression, the system state is weakened and the system will be able to follow other trajectories because the energy required to move the system in a new direction is considerably reduced (Sterman 2000, p 390).

Model testing should be designed to uncover errors to understand the model's limitations, improve it, and ultimately use the best available formal or mental model to assist in important decisions. No model can be verified or validated because all models are wrong. Our choice is only which model to use (Sterman 2000, p 846).

System dynamic modelling is an important tool to understand all the different feedbacks, but using modelling requires that the modeller sets boundaries and simplify the world. The modelling process gives important learning about the importance of the most important feedback mechanisms. The strength of system dynamics compared with traditional models is the dynamic approach where changes in the system are mainly driven by disequilibrium, compared with the traditional models where equilibrium is reached immediately. This is important, primarily because it takes rather a long time to reach stability when a major instability occurs. If it is required to change the entire infrastructure, as a major disequilibrium in supply and demand of fossil fuels could cause, it may take as long as 30 years.

3.4 Valuation, risk and uncertainty modelling

Valuation of opportunities, including risk assessment, is essential for making decisions with respect to investment in new opportunities. Traditional valuation is based on pure economic valuation, by use of Net Present Value (NPV), internal rate of return (IRR) or payback time. These methods are useful when a company is evaluating several investment opportunities, for instance, two or more project concepts. However, it might not be as useful when the company or society is making strategic investment decisions, such as R&D investments in a specific technology development programme. In such a case, real option theory combined with game theory could be more useful (Smit and Trigeorgis 2004). In addition, non-economic values or objectives could also be important decision criteria, such as environmental impact, and inclusion of non-economic objectives opens up a larger range of decision alternatives than pure economic objectives (Keeney 1992). These non-economic values have increasing importance in decision making caused by an increasing focus on corporate social responsibility, but so far, very few decisions made by companies can be traced back to non-economic values alone (Cramer 2006). Maslow's (1952) hierarchy of need clearly describes how basic needs must be satisfied before a person can consider higher needs. The same hierarchy applies for businesses, where financial viability is a basic need that has to be fulfilled before the organisation can consider such things as social responsibility or long-term strategic development.

The standard method for evaluation of project economy is to calculate the Net Present Value (NPV), and evaluate different project alternatives against each other based on NPV. Internal Rate of Return (IRR) and pay-back time are sometimes used as additional information in the decision process because they can give supplementary information to the decision maker about the timing of the future cash flow (Smit and

Trigeorgis 2004, p 11). The NPV method implicitly defines an investment decision as a "now or never" proposition and does not properly take into account the value of a wait-and-see strategy to make decisions as the value of the project evolves and uncertainty is revealed through R&D or market development (Smit and Trigeorgis 2004, p 11).

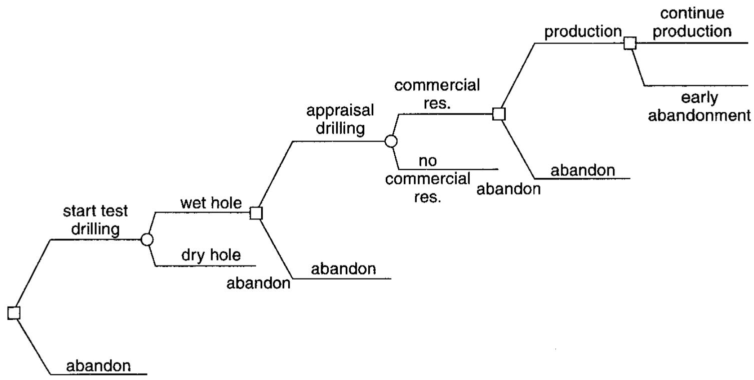
The value of a strategic investment opportunity can be calculated as the sum of the project NPV and the option value, i.e., the value of getting more information. The risks associated with the different investment options are different, indicating that a risk-adjusted discount rate should be different for the different options. Cash flows should first be discounted for the time value of money and then discounted for risk. Investment projects should be discounted for both time and risk while private risk, such as putting the money in a savings account, should be discounted for time only (Mun 2006, p 91). Discounting of a project should also depend on the project owner, as the value of money is fundamentally different in a commercial company, a public project or a private investment.

Previous investments and competencies create path dependencies and constrain the number of future investment opportunities. Innovations in an industry depend on the technological opportunities along future paths and are not exogenous to the industry, and will impact future growth option value (Smit and Trigeorgis 2004, p 51).

An option gives the holder the right, but not the obligation, to buy or develop an asset such as an oil field, a land area or a wind resource (Smit and Trigeorgis 2004, p 98). Real option valuation can be a helpful tool to simplify strategic investment decisions, such as (Mun 2006, p 93):

- Abandon project
- Wait and see
- Delay
- Expand
- Increase R&D effort

The project sequences can be seen as a set of options, and can be described by use of decision trees, where different types of risks are resolved at the different stages. The 'risks' could be uncertainties in factors such as costs, prices and production volumes. Working through the different scenarios, estimating the values and uncertainties, one would eventually end up with a good picture of the different options and the value of these options (Smit and Trigeorgis 2004, p 136-149). An example of a decision tree for an offshore drilling project is given below.



Note: Management has the following contingent decisions (□) or options: The option to start test drilling, to invest in appraisal wells, to invest in development, and to abandon. At the same time, price and quantity uncertainty (○) evolves over the life of the project.

Figure 33: Decision tree for an oil development project (Smit and Trigeorgis 2004, p 137)

Each of the branches in the tree has an associated value and probability, and by starting with the values at the right-hand side of the figure, it is possible to work through the diagram, and essentially to estimate the value of the project at the left-hand side.

Uncertainty can be estimated by use of Monte Carlo simulation, an analytical tool which generates numerous simulations based on a probability distribution of uncertain variables. The probability distributions of the different variables are determined based on both objective and subjective evaluations of the uncertainty of the variable. Examples are uncertainty in oil resources, market growth, and economic growth. This can be done using Excel or other risk-simulation tools, such as the risk modelling application in the PowerSim software. Uncertainty and risk are not the same; uncertainties are resolved through time, while risk is the outcome of uncertainty (Mun 2006, p 140).

Valuation of these opportunities could be done by using simple NPV or IRR analysis, or more sophisticated optimisations based on real option theory. To simplify the analysis, a simple decision tree with different opportunities has been developed, and values of the different scenarios have been calculated. Due to the complexity of the problem, such estimates have to be based on simplifications and assumptions, and will therefore not necessarily represent the absolute value of the opportunity but will give a good indication of the potential of the opportunity for relative value creation.

4 Analysing the future energy market

The challenge for the future welfare in Europe and Norway seems obvious. How can a significant increase in sustainable energy production to secure Norwegian and European energy supplies be achieved? The first step could be to investigate how the future demand, supply and price of energy might develop in different scenarios and different policy regimes. In this thesis, system dynamic modelling and scenario analysis has been used as methods to estimate future European energy prices with uncertainty. Based on the scenario analysis, several strategic directions that Norway could follow to increase national value creation have been evaluated.

4.1 System dynamic modelling approach – the CE2 model

The following section will give a brief description of the CE2-model developed in this study without drowning in details. The CE2-model is a regionalised model that couples climate, energy and economy. The CE2-model is based on the theories and analysis from chapter 2. The CE2-model has been developed using PowerSim Studio7 developed by PowerSim AS (www.powersim.com). The CE2-model is available at www.pikarstad.com.

> The journey is the destination in integrated modelling (Fiddaman 1997, p 190).

The modelling process is as described by Fiddaman above, more important than the final model. The process of modelling leads to important insights in the main feedback processes of the system and how system components interact over time.

Several models are developed for the energy system for different purposes. Most of these models are based on linear programming and economic equilibrium. Institutions such as IEA and IPCC use MARKAL and TIMER as the basis for their analysis of the future energy market (Gether 2004, p 119-126; ETSAP 2008) while MESSAGE (Schrattenholzer, Miketa et al. 2004) was used by IIASA to predict future energy scenarios. Nordhaus and Boyer (2000) developed the DICE and RICE models, which are equilibrium models for global and regional economic development given different policy options. The system dynamic thinking and modelling in this work is mainly based on three models:

- WORLD3 (Meadows, Randers et al. 2005)
- FREE (Fiddaman 1997)
- EICOMP (Gether 2004).

Some variables and assumptions in the models are difficult to validate or estimate due to limited public data and are subject to large uncertainties. Given the uncertainties related to future social, economic, political, and institutional changes, it is impossible to provide accurate forecasts (Nordhaus and Boyer 2000, p 53). However, even if the models cannot provide good forecasts due to these uncertainties they force us to reveal assumptions about the real world (Toth 1995 quoted in ; Fiddaman 1997, p 13).

> We use the computer for its primary purpose – not to predict what will result from current policies, but to ask what could happen if we make various changes (Meadows, Randers et al. 2005, p 10).

In this thesis, the primary market is the European energy market. Energy production capacity in Norway exceeding Norwegian energy consumption will contribute to European energy security as long as there is sufficient export capacity. Improved European energy security will require increased domestic energy production, energy efficiency improvements and geopolitical stability in the major energy producing regions. Avoiding severe impacts of climate changes will require a set of energy and climate policies, including carbon pricing, regulation of carbon emissions, and energy efficiency targets to reduce both end-user consumption and energy losses in the energy value chain.

The CE2-model is initialised with data from 1960 to capture and model the historical behaviour up until 2000. The CE2-model, with the history-matched parameters, is then initialised and restarted in year 2000 and predictions of future developments are run until 2100. The CE2-model is unlikely to predict with certainty 100 years into the future, because technological breakthroughs will become available within this period that completely alters the predictions. Wars and natural catastrophes may also lead to a change in the path of the energy system in this period. However, the CE2-model may give some indications of the future developments given the assumptions and beliefs in the model.

> The art of model building is knowing what to cut out (Sterman 2000, p 89).

The energy market and the climate issue are global challenges. The problems of limited fossil energy resources and the geopolitical issues related to an increasing concentration of petroleum resources in the Middle East and North Africa will influence the entire fossil energy security situation. This is expected to have significant impact on the availability of fossil fuel, supply-demand balance and energy prices in all markets. The dominant economies in the next 50 years will be located in Asia and the Pacific. The growth in these economies, and the associated growth in energy demand, will have a significant impact on energy systems, energy security and prices in the long term. Ignoring these economies and their requirements for energy also ignore the main drivers for energy demand growth. Understanding future developments in the European energy markets will require a global view.

The main boundaries of the CE2-model can be described by the following table:

Endogenous Parameter	Exogenous Parameter	Excluded Parameter
Population growth rate	Labour force fraction	Bio fuels
Labour force	Interest rate	Hydrogen
Capital investment	Value share of capital	Sector energy demands
Depreciation due to climate change	Factor productivity	Non-commercial energy use
Energy efficiency index	Capital lifetime	
Operating capital	Energy labour force	
Energy efficiency improvement rate	Capital cost due to temperature change	
Energy demand	Capital cost due to sea level rise	
Energy Price	Energy resources	
CO_2 flux out of atmosphere	CO_2 tax introduction	
CO_2 concentration	CO_2 market introduction	
Temperature change	CO_2 emission rights	
Sea level rise	CCS introduction	
CO_2 emissions		
Energy capital		
Energy production		
Energy import		
CO_2 price		
Learning curves in energy sector		

Table 6: Key parameters in the CE2-model

The emphasis in this thesis is the long term energy supply. It is assumed that there is long-term substitutability between all energy sources and carriers, based on end-user costs and energy availability. Historically, this has not been the case, particularly in the transport sector, but this is likely to change soon as a consequence of new battery technologies (IEA 2008a).

The subsystem diagram below illustrates the architecture of the CE2-model. The CE2-model is divided into five regions; Norway, EU, Asia-Pacific, North-America and Rest-of-world. Norway is small compared with the other regions, and could be modelled as a part of the European (EU) region, but has been treated as a separate region due to the focus of this work. The modelled development in the European energy market is the basis for the valuation in the next chapters. However, it could be useful to split Rest-of-world into several regions, with Russia, the Middle East and North Africa of particular interest due to their energy resources and geopolitical position.

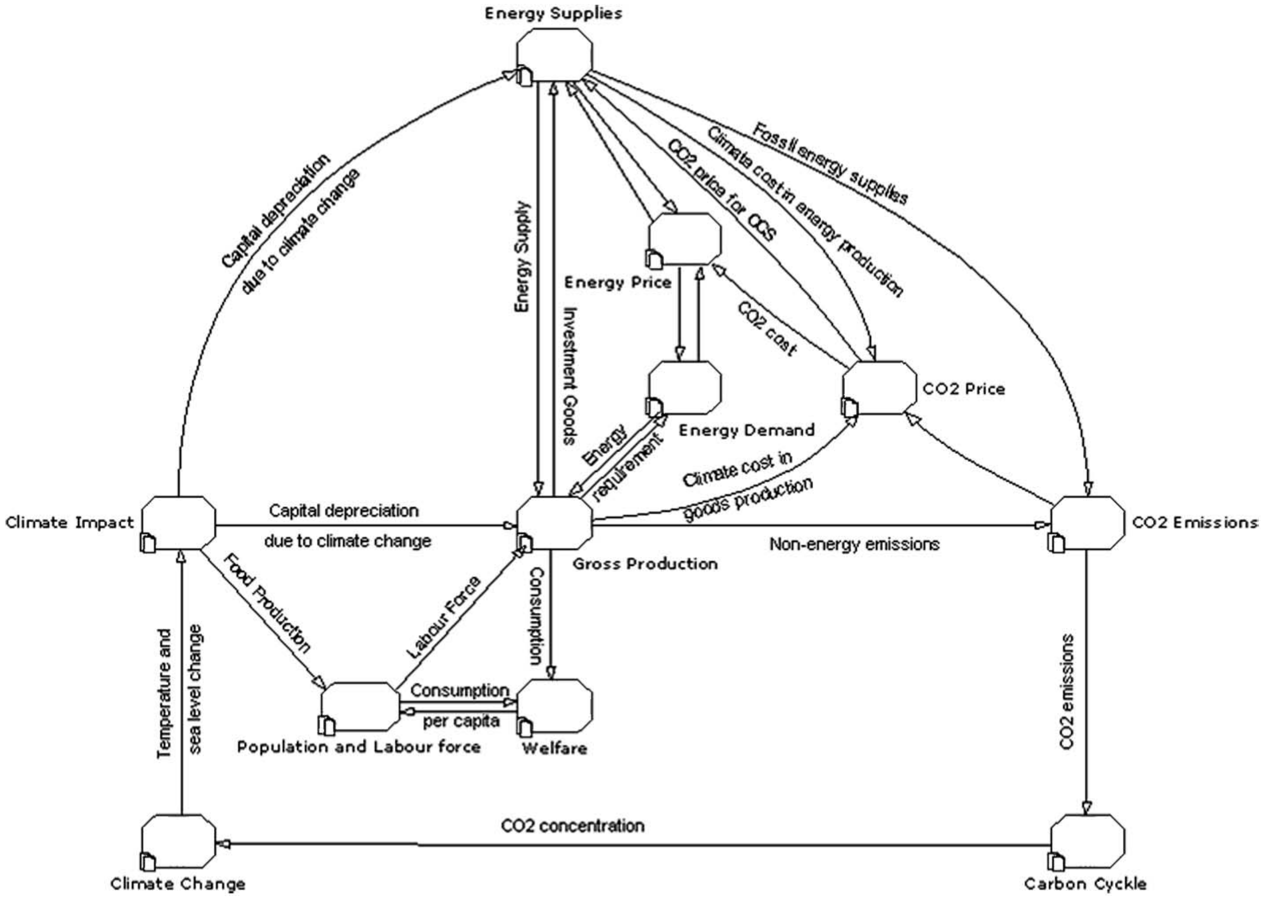


Figure 34: Main sub-structure of the CE2-model

The combined effect of path dependence and lock-ins, caused by long lead times, is a major challenge related to creating shifts in the energy system. This is mainly a consequence of previous investments in production capital and infrastructure with a rather long lifetime, typically 25 to 50 years. These facilities represent sunk cost and are unlikely to be abandoned unless there are dramatic changes in the world, such as war and catastrophic events that destroy the capital and open the way for new types of energy capital. Path dependence is caused by dominating positive feedback processes in the system working as growth engines, which creates lock-ins because it is difficult to break out of these positive feedback processes (Sterman 2000, p 364-379). The feedback structure of the model determines its dynamics, and efficient policies would have to change the dominant feedback loops of the model, to shift from one dominant feedback loop to another (Sterman 2000, p 104).

The main stock and flow structure of the CE2-model are illustrated in figure 35 below.

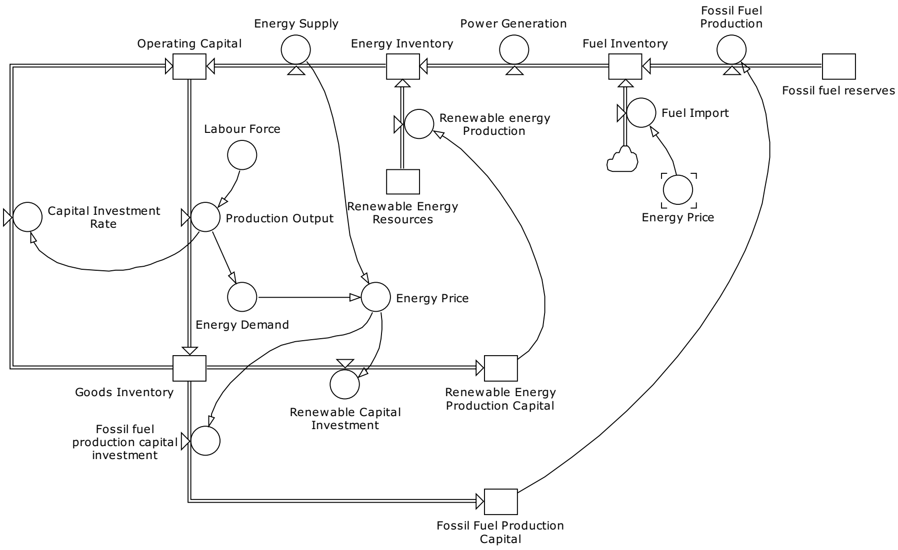


Figure 35: Main Stock and Flow structure of the CE2-model (simplified illustration)

4.1.1 The simulation model

To simplify, it is assumed that an economy in principle produces two types of output; goods and energy. The total output is equal to the sum of production output and energy output. The inputs to production of both goods and energy are capital, labour and energy. The capital and energy input have to be taken from the total output. The output of goods can be used for three purposes; investment in capital for goods production, investment in capital for energy production, and/or consumption.

4.1.1.1 Economic development

The economic model used in this thesis is based on Fiddaman (1997), and the outline of the main structure of the capital accumulation in the economic sub model of the CE2-model is as described in figure 36. The economic sub model used in the CE2-model is a standard Cobb-Douglas equation, with normalised parameters to the start of the simulation (Solow 2000). Capital is accumulated based on a standard model approach, where capital investment flows into the capital stock and where capital depreciates based on the lifetime of the capital stock (Fiddaman 1997; Gether 2004).

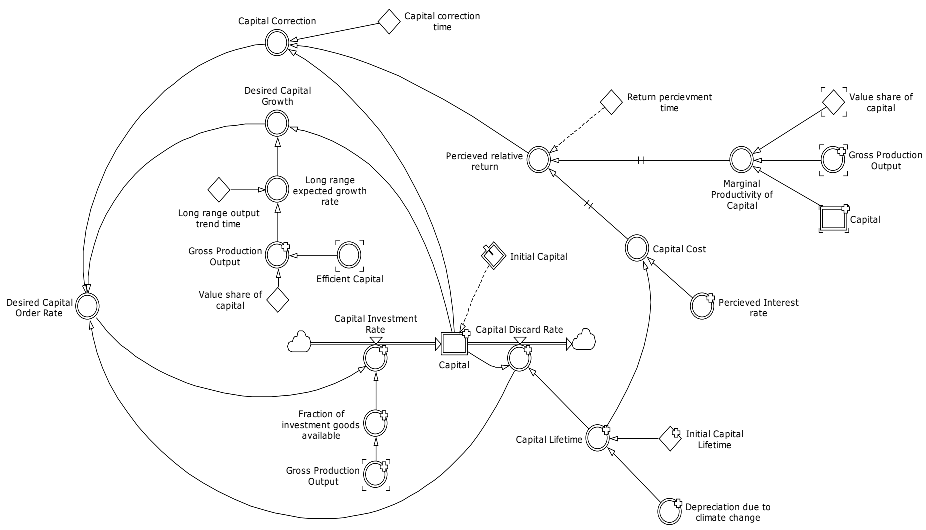


Figure 36: Capital accumulation in goods production

Capital lifetime in this model is determined by two factors; the "initial capital lifetime" and "depreciation due to climate change". Capital cost is the sum of the interest rate and depreciation rate.

Factor productivity is calculated based on an exogenous constant annual improvement rate. However, average factor productivity is calculated as a co-flow to capital accumulation which incorporates the fact that technological improvements are embodied in new capital investments resulting in zero productivity improvement if there are no investments in new capital.

4.1.1.2 Population growth

Fiddaman (1997) recommend that key subsystems like population should be modelled endogenously, to gain insights that are not available from the exogenous forecasts used in most models. For population growth, WORLD3 describes these endogenous feedbacks and includes how the population develops as a function of welfare, food availability, urbanisation and pollution (Meadows, Randers et al. 2005). The WORLD3 model gives a better response to population changes caused by welfare changes than most of the other models applied in this type of modelling. The population growth sub model in the CE2-model has been calibrated to current data for expected lifetime and fertility (WorldBank 2006).

4.1.1.3 Energy demand

Energy requirements for the economy are embodied in the capital stock (Sterman 1981; Sterman 2000). The rates of installation and discard of energy requirements are co-flows with capital investment and discards where energy efficiency improvements in new capital reduce the average energy requirements of the capital stock.

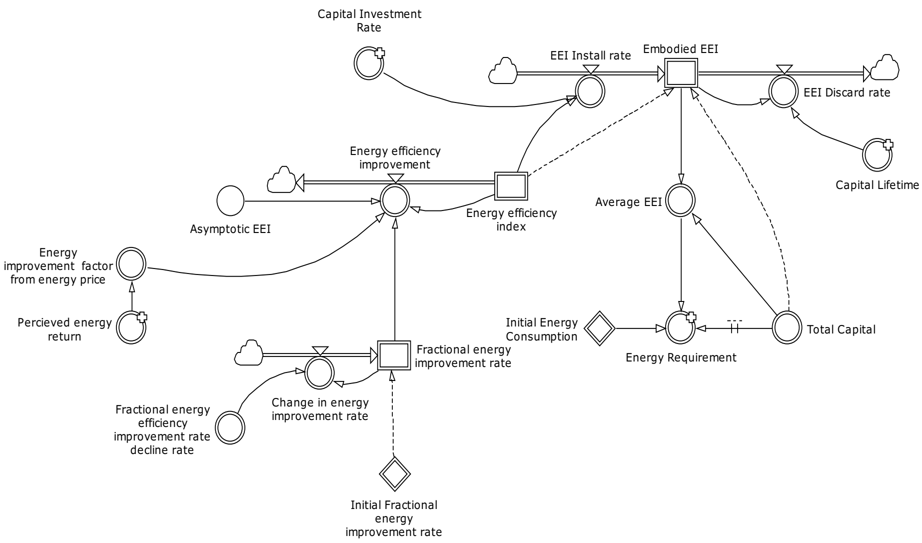


Figure 37: Energy Efficiency Improvement model (EEI)

The different energy sources and carriers are not highly substitutable in the short run (Fiddaman 1997, p 84-87). Both Fiddaman (1997) and Gether (2004) modelled the demand for different energy sources based on changes in capital stocks for each energy carrier. Gether (2004) modelled the demand side from households, transport and industry in detail to identify change in demand for different energy carriers. Since the lifetime of the energy-consuming goods is quite similar to the lifetime of the energy production and distribution infrastructure, the change towards a sustainable energy system is likely to be equally limited by the energy capital replacement rate as by the end-user capital replacement rate. It is likely that the energy infrastructure will be increasingly electrified, as will transportation, and in the long run a high degree of substitution between energy sources and carriers is expected. Energy demand is therefore linked to the production capital, which defines end-user energy consumption. Energy demand is equal to energy requirement reduced by a factor calculated as the marginal value of energy divided by energy price. If energy price is lower than the marginal value of energy, then energy demand equals energy requirement, while an energy price above the marginal value of energy will reduce the energy demand accordingly.

4.1.1.4 Operating capital

Operating capital is defined as the capital available to produce output as described in chapter 2.2.2. Operating capital is determined by the share of energy requirement delivered to produce output, where the energy value share defines how important energy supplies are in the relationship between operating capital and physical capital. Fiddaman (1997) use an energy value share of a capital-energy-aggregate of 0.185. Assuming that the marginal value of energy is approximately equal to energy price would require a higher value share of energy to reproduce recent historical energy consumption. In the CE2-model an energy-to-capital elasticity of 0.36 has been used. The value reflect the marginal value of energy in operating capital as experienced in recent years indicating that an energy costs up to 10 % of the aggregated production cost is acceptable for society.

4.1.1.5 Energy supplies

For all types of energy production, the general production function as described chapter 2 has been used as a basis for developing the set of equations necessary to model the energy system. For the energy production system it is assumed that labour requirements are constant relative to capital. This assumption is fairly accurate on the time perspective of this work. Capital accumulation for fuel production, energy production, and energy distribution is based on the same principal model as that described for goods production.

The behaviour of the energy system is influenced by the evolution of technology, where small, early decisions might have great impact due to positive feedbacks that create path dependence and lock-ins (Fiddaman 1997, p 195). In the CE2-model, it is assumed that costs decline as industries gain experience. These learning curves describe the technological progress as a function of accumulating experience with the production and the use of a technology assuming 20 % productivity improvement for each doubling of cumulative investments (Löschel 2002).

While technology improvements will have a cost-reducing effect on scale economies, depletion and saturation will increase costs in the energy sector (Fiddaman 1997; Gether 2004). As energy resources become scarcer a significant cost increase will be experienced because an increasing amount of capital and labour will be required to produce each unit of energy supply.

The CE2-model includes four different renewable energy sources; hydro power, onshore wind, offshore wind and solar power. The commercial potential of these energy sources will depend on three major factors; energy price including CO_2 tax, subsidies and learning curves. The CE2-model is calibrated to current unit costs and production capacity.

Fossil-fuel production is in principle modelled the same way as renewable energy production, where learning curves and capital accumulation represent the main factors for production capacity. A more complete system dynamic model of the petroleum life cycle has been developed by Davidsen et al (1990). Their model is capable of modelling the behaviour of the US demand and supply of crude oil through the history of petroleum production and represents a good basis for understanding how petroleum resources are brought to the market through exploration, development and production. On the other hand, Tao and Li (2007) used a very simple system dynamic model to investigate the future peak in China's oil production, and demonstrated how simple analysis of specific and important issues can be done by use of system dynamics.

The CE2-model includes four different fuels; oil, gas, coal and nuclear. In addition to fuel production capacity, the model includes import and export capacity of fuels, and a separate model for transforming primary energy into end-user consumable energy such as electricity. For simplification, it is assumed that half of the gas and coal consumption are used in power generation. The fuels are then delivered to the power generation facility, where capacity is determined by capital and learning curves, to generate end-user energy, normally in the form of electricity. Power generation has an energy loss of 50 % to 70 % which is removed from the stream while the remaining energy flow is delivered to the consumer (Gether 2004).

4.1.1.6 Carbon capture and storage

Carbon capture and storage (CCS) is based on the same basic model as energy production, where capital accumulation and learning curves determine the production capacity. Marginal production value is determined by the production capacity and the price of CO_2. The willingness to invest in CCS is determined by the relationship between the marginal value and capital cost, which eventually determines the capacity for CO_2 removal and utilisation.

4.1.1.7 Pricing and allocation of capital, labour, energy and carbon

Capital and labour are allocated to energy investments first, and then to investments in goods production. The remaining capital goods from production is allocated for consumption. If there are surplus of goods or energy, it can be exported to other regions, provided that there is available export capacity. The pricing of energy and CO_2 emissions are calculated based on a simple price model described by Sterman (2000, p 541). The same basic model is used for CO_2 pricing, where supplies are replaced by emission rights and demand by actual emissions. The price of power generation and import-export is determined by use of a constant mark-up or tariff of 15 %.

4.1.1.8 CO_2 emissions

CO_2 emissions from energy are calculated based on fuel consumption and fuel loss within a country or region, multiplied with the CO_2 content per fuel unit. Non-fuel greenhouse-gas emissions are expected to grow by a function equal to the square root of the relative growth in economic output. Any utilised CCS capacity is subtracted from the total emissions, to calculate the volume of greenhouse gases emitted to the atmosphere.

4.1.1.9 Carbon cycle

The natural carbon cycle is a complicated process that involves the accumulation of carbon in the atmosphere, the biosphere and the ocean. This process has been modelled in a simple model in DICE (Nordhaus and Boyer 2000) and as a more realistic model, reflecting the actual processes, in FREE (Fiddaman 1997, p 115). In the CE2-model, a simplified model based on FREE has been used as the basis for the scenarios. The CE2-model has two base elements; CO_2 flux from the atmosphere to the ocean/biosphere to re-establish equilibrium between atmosphere and ocean, and CO_2 flux from ocean to atmosphere due to warming of the ocean. The CE2-model reproduces historical CO_2 concentrations quite well, and reproduces the future behaviour of FREE and IPCC (Fiddaman 1997; IPCC 2007a, p 803) .

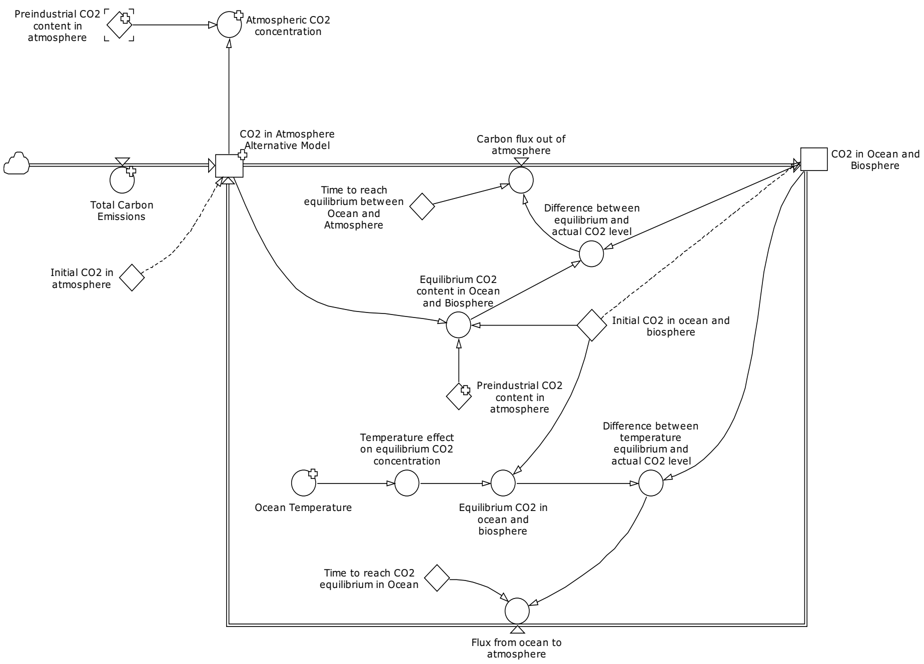


Figure 38: Carbon Cycle in the model

4.1.1.10 Climate change

Climate change in this context would be an estimate of atmosphere and ocean temperature based on the concentration of CO_2 in the atmosphere. The simple approach would be to use the simple model proposed by IPCC (2007a) to estimate atmospheric temperature. The climate change model used in the CE2-model is based on the IPCC model (2007a) but includes in addition ocean temperature as modelled by Fiddaman (1997, p 122). The intention is to be able to include the important flux of CO_2 from ocean to atmosphere caused by increasing ocean temperature in the carbon cycle. The rate of ocean warming can be determined by the heat capacity of the atmosphere and the ocean and the temperature difference, indicating a heat mixing time between atmosphere and ocean of approximately 250 years.

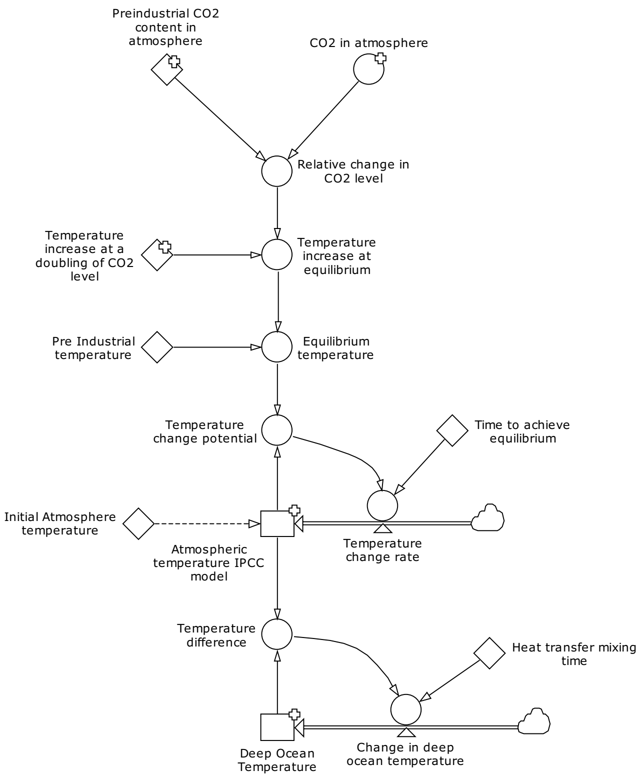


Figure 39: Temperature Change model

4.1.1.11 Climate impact

The main principle for climate impact used by Fiddaman (1997) has been incorporated into this work. This principle assumes that the climate impact is a function of the difference between the actual temperature and the temperature to which society has adapted (Fiddaman 1997, p 124-127). An adaptation time of 100 years has been assumed. This is probably too long, based on two arguments. First, in a situation with severe climate change, there will be no options other than to adapt as soon as possible, which would mean as soon as the society is capable of replacing damaged capital goods and restoring productivity. Second, because all capital goods are replaced within a certain timeframe, usually 40 to 50 years, it is in principle possible to adapt to all changes within this timeframe.

The climate impact is calculated as an increase in capital depreciation rate, which is based on the argument that climate change accelerates destruction of capital goods, and agricultural areas. This means that an increased portion of the production output has to be used for replacing damaged capital due to climate change. This will also increase the total capital cost of energy and goods producing capital. The depreciation rates are calculated based on Nordhaus's (2000) estimate of productivity loss.

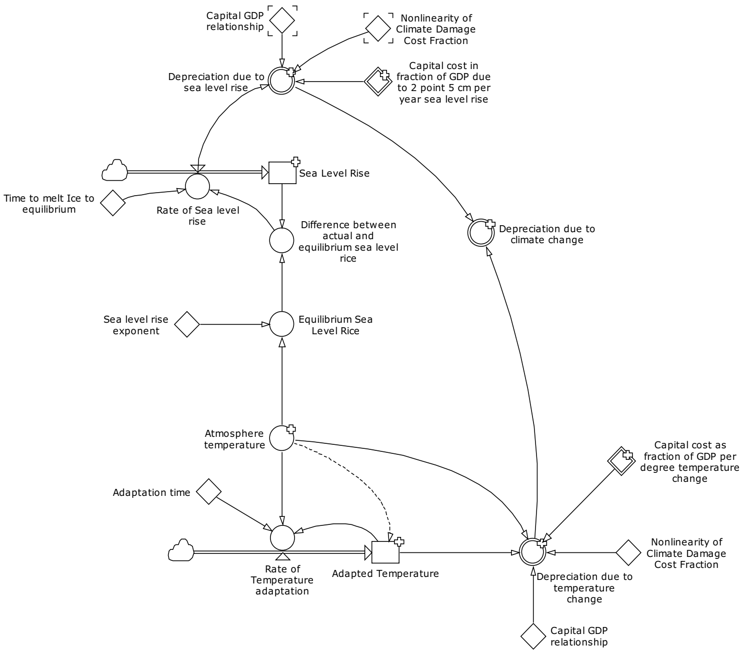


Figure 40: Climate Impact model

The CE2-model calculates two effects, depreciation due to sea level rise and depreciation due to temperature change, and the different regions experience different impacts from these two effects. The actual numbers used in the model are taken from Nordhaus and Boyer (2000) and IPCC (2007b, p 787). The impact of climate change on food production was originally included, but has been removed as it seems to have relatively low impact at temperature changes below 3–5 ^{o}C (IPCC 2007b, p 787).

4.1.2 Data sources

World Development Indicators (2006) by the UN have been used for the historical development of economic output and population, while BP data (2007) has been used for historical energy production and consumption. Resource potentials are estimated based on several sources, as discussed in Chapter 2.

4.1.3 Model testing

Model testing is necessary to ensure that the model reproduces the behaviour adequately to understand the problem to be solved. The main purpose of the testing is to uncover errors, understand the limitations of the model and improve important areas to include the major feedback mechanisms. To do so, the model should be robust under extreme conditions, it should reproduce the historical behaviour fairly well and sensitivities should be used to understand different boundary conditions of the model (Sterman 2000, p 846).

4.1.3.1 Historical behaviour

The CE2-model is adjusted to fit history from 1960 to 2000, using World Bank Development Indicators (2006) and BP data (2007) for energy production and consumption, and the CE2-model is capable of modelling the major trends during this historical period. Due to the major impact of energy policy and geopolitical stability on energy investments and production, which lead to an uneconomic behaviour in the real world, reproduction of history is difficult on a regional level. The purpose of modelling has not been to predict the future, or model the exact behaviour into the future, but to understand how different policies might influence the energy system, and how society could respond to such changes. The modelling process has given insight into the complicated feedback processes between economic growth, energy supplies and environmental impact of energy consumption. The simulation runs for the historic period 1960–2000 are illustrated in the figures below:

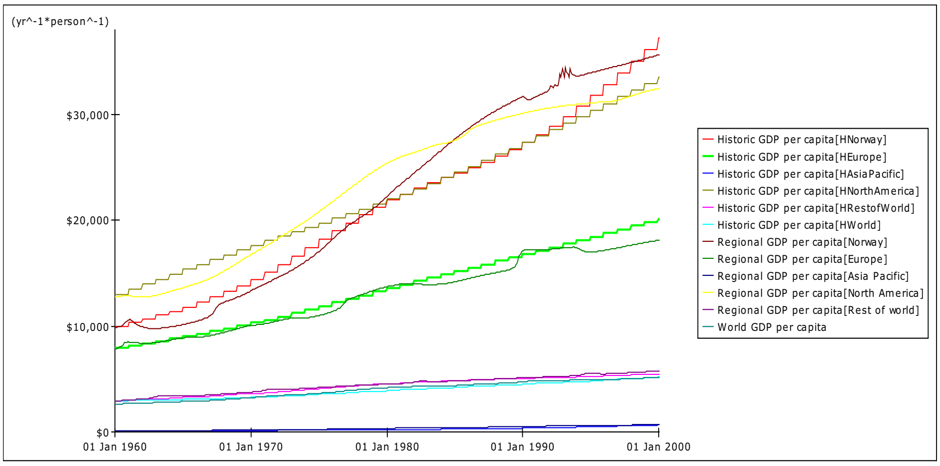


Figure 41: Regional and World GDP per capita

There is quite good fit between measured and modelled GDP per capita and differences are mainly caused by developments in energy prices and technological progress.

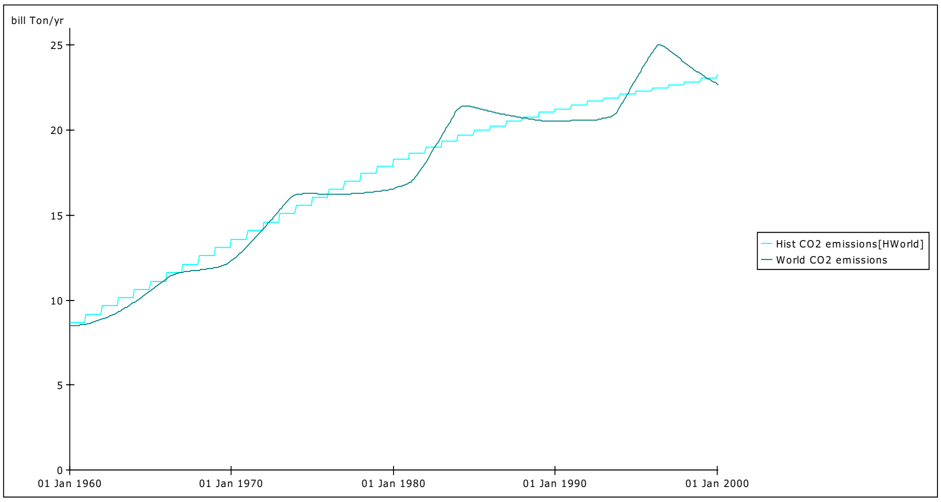


Figure 42: Global CO_2 emissions

The global CO_2 emissions are at the same level but oscillate more than the historical data. This is related to the political influence in the real world on fuel production capacity in the Middle East and Russia. There are discrepancies on the regional level, probably caused by reporting issues, the balance between different energy sources, and energy efficiency in the entire value chain. For Europe and Norway, there seems to be a rather good fit.

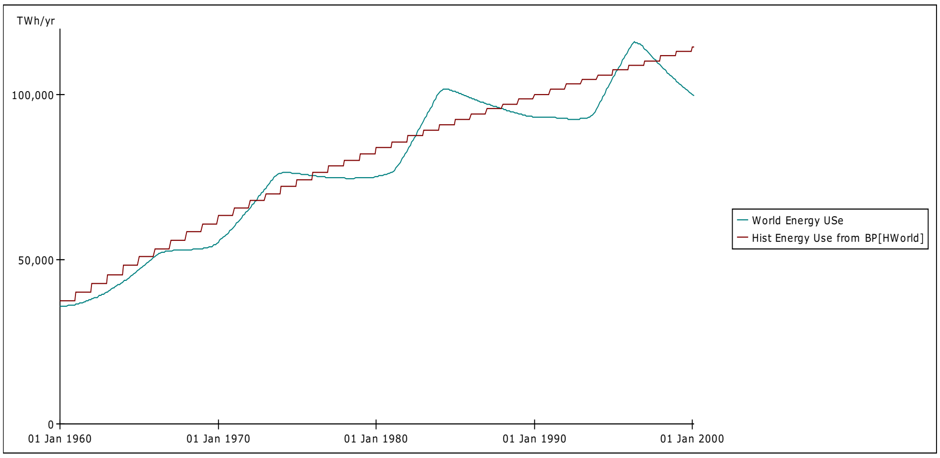


Figure 43: World Primary Energy Use

The CE2-model reproduces the world primary energy use, and the regional energy consumption, production and import/export quite well. Oscillations are mainly caused by policy influenced energy investments and modelled prices in Rest-of-the-World.

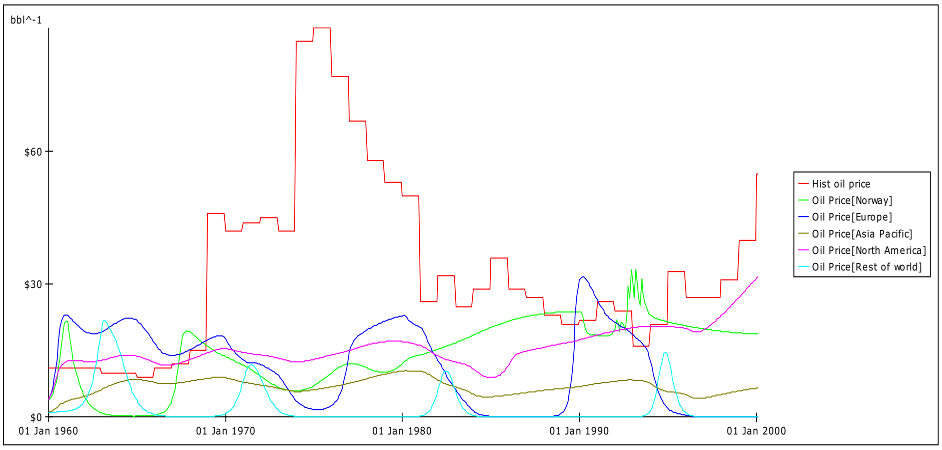


Figure 44: Modelled Oil Prices

The high price levels in the 1970s and 1980s are caused by political events and do not represent a balanced price reflecting the marginal cost levels. However, the lower historical prices might reflect marginal costs. The modelled low oil prices in Rest-of-the-world are due to the fact that production capacity in this region is controlled by export prices, and the regional markets are heavily subsidised. Decisions to invest in this region are controlled by the export price in the market and national policies.

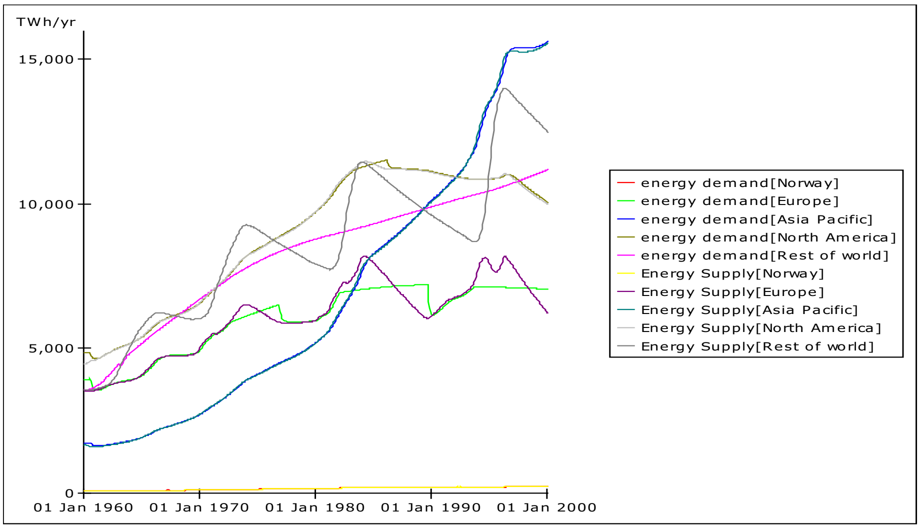


Figure 45: Modelled energy supply and demand

The CE2-model balances demand and supply in different regions quite well as illustrated in figure 45 above, except for the oscillation in the Rest-of-the-world region.

A perfect history match is difficult to achieve when the model are dominated by endogenous variables as here. A model that correspond to history is not necessarily more useful for predictions than a model with poorer history match (Sterman 2000, p 878-879). A good history match is only relevant if the main drivers and feedback mechanisms of the history is relevant for the future behaviour of the system. In the case of the energy system, it is likely that the feedback mechanisms in the future will be different from the historic mechanisms, leading to the conclusion that history may be less relevant for the modelling of the future energy system.

4.1.3.2 Future energy prices

Many agencies, such as IEA (2007), assume a constant oil price for the foreseeable future. This assumption is unlikely. This will lead to supply abruptions in the model as this price does not meet future marginal costs. The price model used in this thesis is based on a supply/demand balance which adjusts continuously to balance supply and demand. The CE2-model results in the prices as illustrated in figure 46 below in a simulation with the base assumptions of climate impact and fossil energy resources. The reference simulation assumes no climate mitigation efforts such as carbon tax and emission regulations.

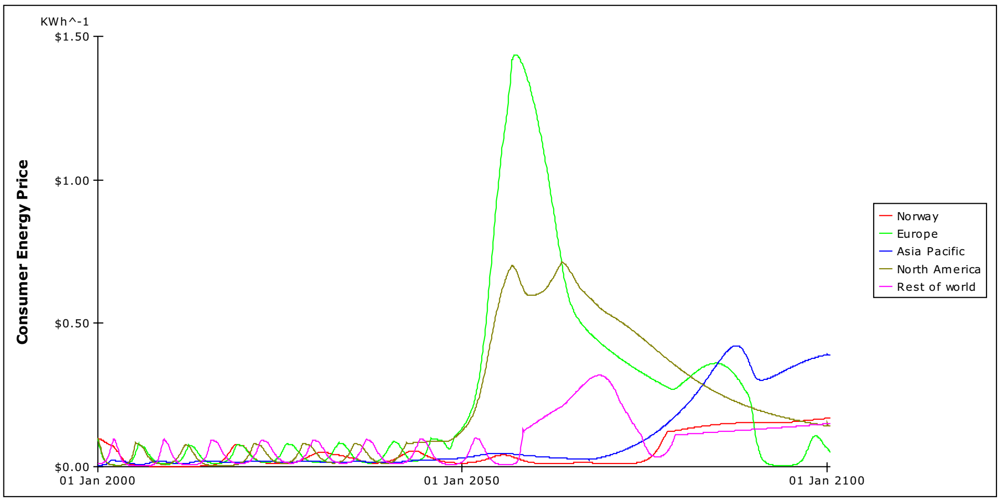


Figure 46: Modelled future energy prices

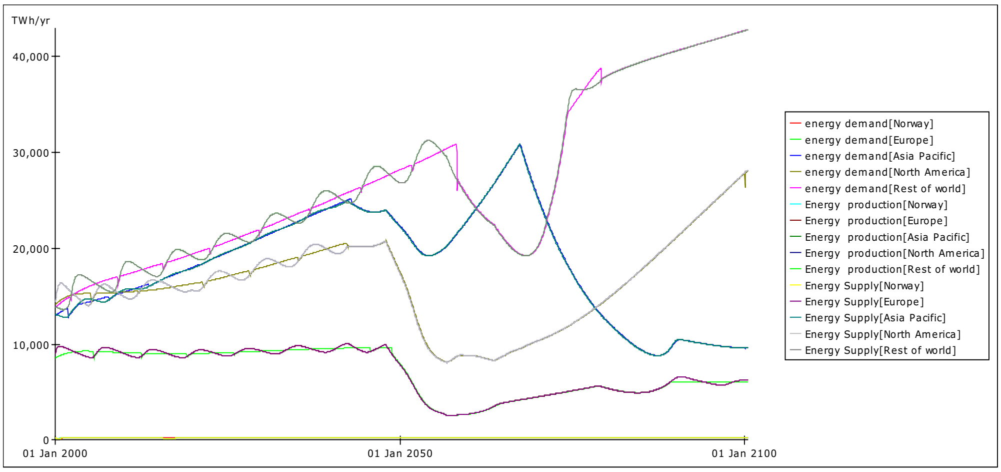


Figure 47: Modelled energy supply and demand

As the CE2-model indicates, there will be a significant price increase as increasing scarcity of fossil energy resources are experienced, in this case around 2050. This price increase will result in decreased energy demand and a period with insufficient energy supplies caused by the long lead time to establish sufficient volume of new energy production. There will be reductions in goods production of up to 20 % caused by energy prices above marginal energy value. The high energy price levels leads to energy efficiency measures, increased renewable energy production and learning effects in renewable energy production that contribute to decreased energy prices in the long run. The world end-user energy supplies are illustrated in figure 48 below. It is important to notice that society would need 20 to 30 years to re-establish sufficient energy production from renewable energy sources to continue the economic growth after peak petroleum. North America, Europe and Asia-Pacific will experience a decrease in goods consumption during this transition period from fossil-based energy to renewable energy sources caused by high energy prices. Asia-Pacific is very vulnerable to this energy supply disruption, because the per-capita purchasing power remains quite low and an increasing share of a rather low per capita output would have to be used to import energy. A tighter fossil energy resource situation will lead to increasing energy prices earlier, leading to accelerated energy efficiency improvement and renewable energy production. Sensitivities on fossil-fuel resources indicate that the production output will decline as "peak petroleum" is approached. "Peak petroleum" will cause a shock in the economy due to insufficient supplies, and last for two decades before the economy regains its productivity based on improved energy efficiency and renewable energy production. The negative impact of "peak petroleum" can be reduced significantly by appropriate planning that aims to diversify energy supplies in type and geography.

Figure 48: Global renewable energy and total energy end use.

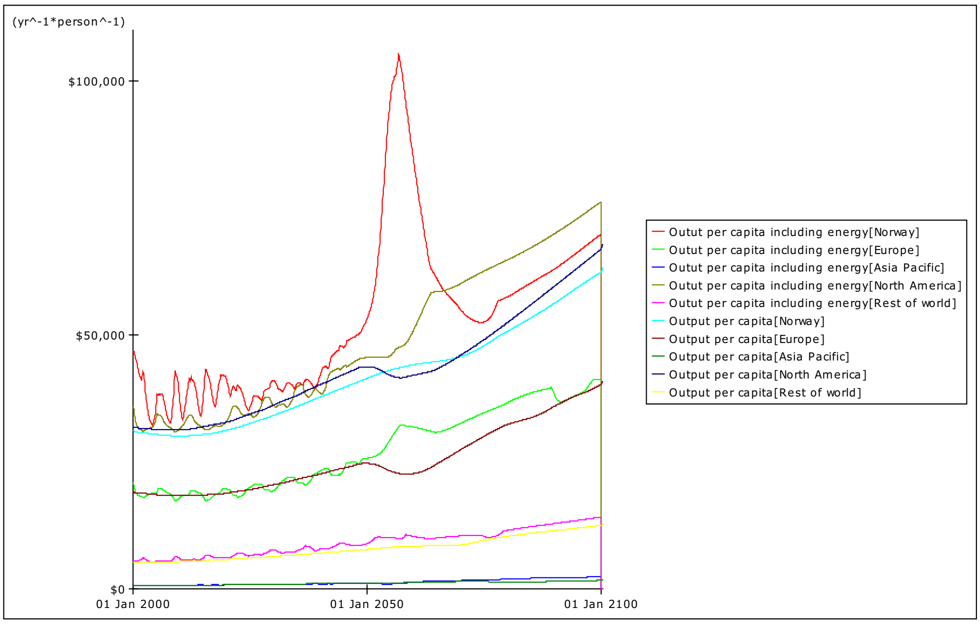


Figure 49: GDP per capita with and without energy.

The final observation is that the energy share of world output is predicted to increase threefold around 2050, from around 5 % of output to 15 %.

4.1.3.3 Reference case with uncertainty in energy and climate

Modelling future energy markets is a highly uncertain exercise, where many elements are difficult to validate or estimate.

> It is probably impossible to provide accurate long-run projections given the rapid rate of social, economic, political, and institutional changes (Nordhaus and Boyer 2000, p 53).

The total uncertainty in the reference case is based on a situation where there are no policies to avoid CO_2 emissions. This reference case represents a simulation that displays the total uncertainty related to energy resources, future climate change and future energy requirements as described in the previous sections.

The uncertainty in energy supplies is mainly influenced by four factors; the fossil energy resources available, the rate of energy investments, energy learning curves and geopolitical stability. The uncertainty in energy resources used here is as described in Chapter 2. The learning curves are assumed to have an expected level of 20 % improvement for each doubling of capacity with a low estimate of 10 % and a high estimate of 30 %.

Uncertainty in the climate system is mainly related to three factors; the carbon cycle, climate change due to increasing CO_2 concentration and the impact of climate change. The uncertainty in the carbon cycle is mainly related to the changes in the equilibrium between atmosphere and ocean which potentially could slow down the net flux of CO_2 to the ocean as the ocean warms. The uncertainties related to climate change caused by increasing CO_2 concentration are described in Chapter 2, and are based on IPCC (2007a) estimates. The impact of climate change is based on estimates from IPCC (2007a) and Nordhaus and Boyer (2000). All parameters are modelled as a normal distribution.

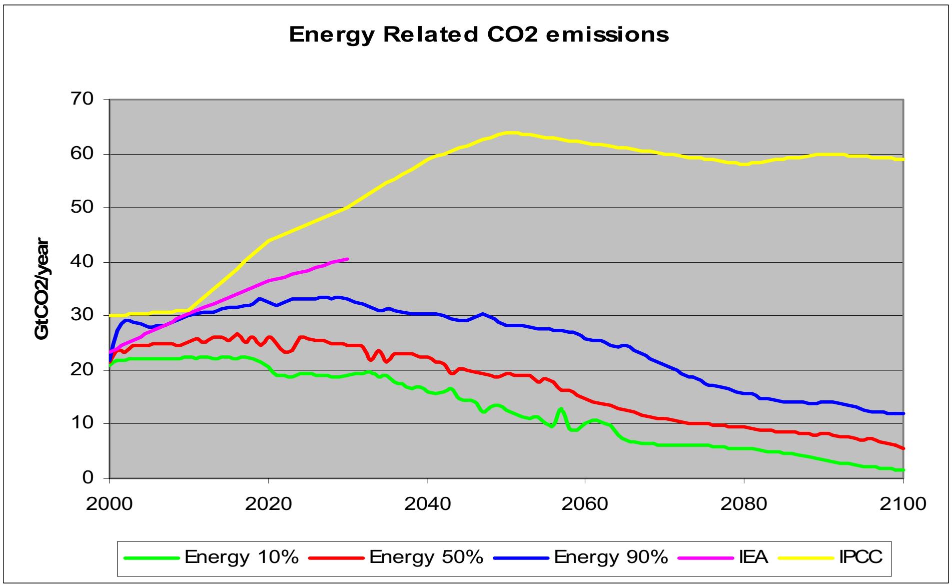


Figure 50: Global energy related CO_2 emissions from the model compared with IPCC and IEA estimates (IPCC 2007a; IEA 2008b, p 402).

As illustrated in figure 50, the simulated energy-related CO_2 emissions will increase in the next two decades. Then this will gradually decrease as a consequence of limited availability of fossil-fuel resources leading to a CO_2 concentration at between 600 and 750 ppm in 2100, with a temperature at 2.8°C above pre-industrial temperature. The high and low estimates are 3.8°C and 1.8°C respectively, as shown in figure 51. The latest resource estimates from IEA (2008b, p 402) would lead to slightly higher levels of emissions and climate change than those presented here assuming that humankind will consume all available fossil fuels without applying CCS. Reproducing the emissions scenario presented by IPCC (2007a, p 803) requires resource estimates three times higher than those used in this thesis.

> Global warming may be acceptable and preferable compared to the socio-economic consequences of not exploiting fossil fuels to their full technical potential (Nel and Cooper 2008).

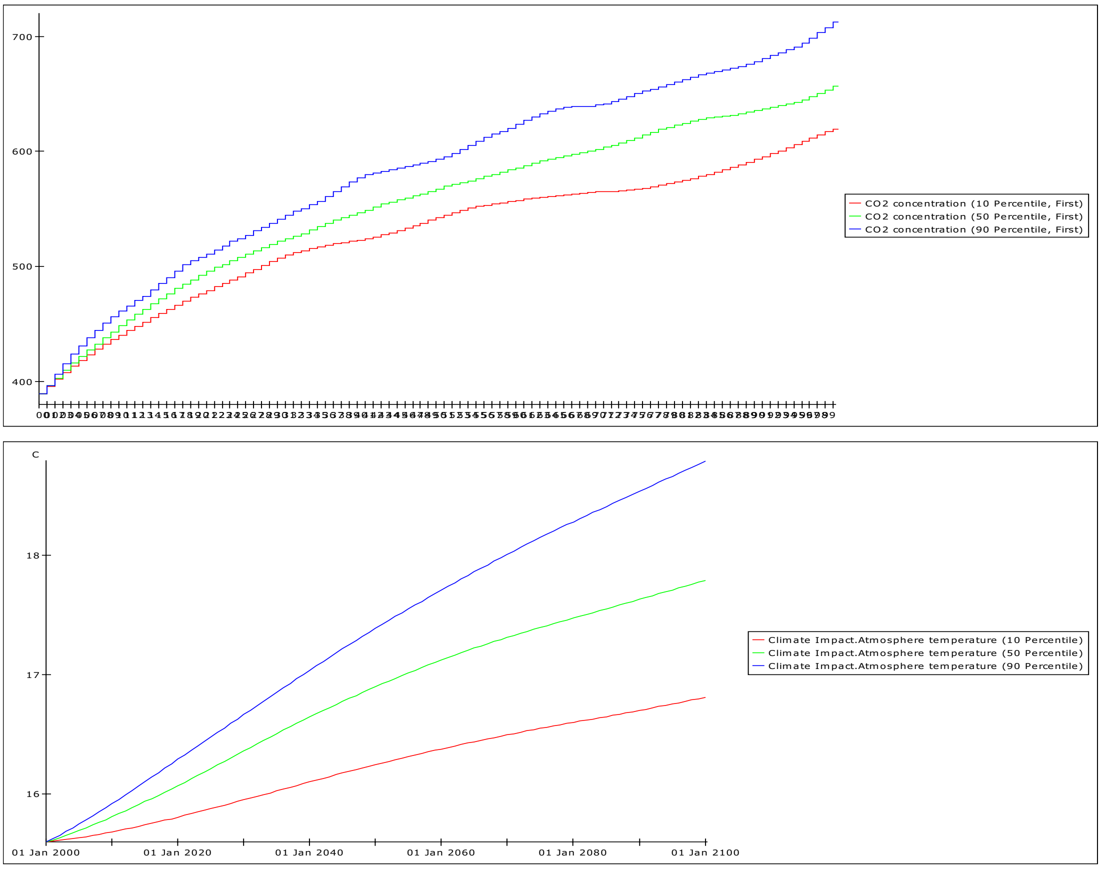


Figure 51: CO_2 concentration and atmospheric temperature

The associated climate cost in Europe is estimated to be between 1 % and 10 % of GDP at the end of the century with an average of 4.2 %, but still increasing as illustrated in figure 52. The sea level is expected to rise by approximately 0.6 metres, but with an initiated increase towards an equilibrium level of 6 to 7 metres in sea-level. The atmospheric warming due to increased CO_2 concentration will contribute to a substantial heating of the oceans, resulting in a major CO_2 flux from the oceans to the atmosphere, which might cause more heating of the atmosphere in the long term than anthropogenic CO_2 emissions. It is likely that a temperature increase above the P50 estimate will cause a severe negative impact on food production in the next century unless technological progress contributes to a major shift in productivity of food productivity and water security.

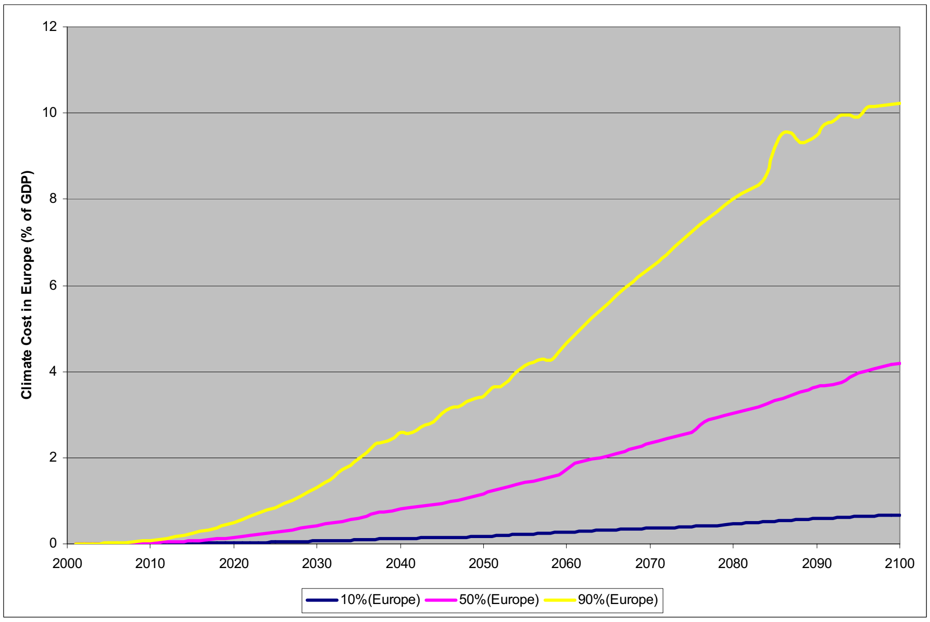


Figure 52: Climate cost in Europe in as % of GDP

As figure 53 below illustrate, the major effect of these uncertainties on per capita GDP is approximately +/-10 %. The peak in fossil-fuel supplies will lead to stagnation in European growth for several decades. The simulations in this study show that the European energy market gradually moves from oil and coal towards natural gas up until 2040. Around year 2040 a shift towards renewable and coal are seen as a response to peak petroleum with an associated rise in energy prices. Oil consumption decreases gradually from around 2020. Energy prices are expected to increase substantially from around 2035, and stabilise around $ 0.4/KWh, which is approximately 5–10 times higher than current European energy prices. The impact of energy resources on production output is close to neutral compared to a case with unlimited fossil-fuel resources, but the fraction of energy costs to total consumption increases substantially and leaves less to goods consumption. As renewable energy sources replace the fossil fuels, the economy seems to recover and at the end of the twenty-first century the economy is at the same level as in a simulation with unlimited fossil fuels.

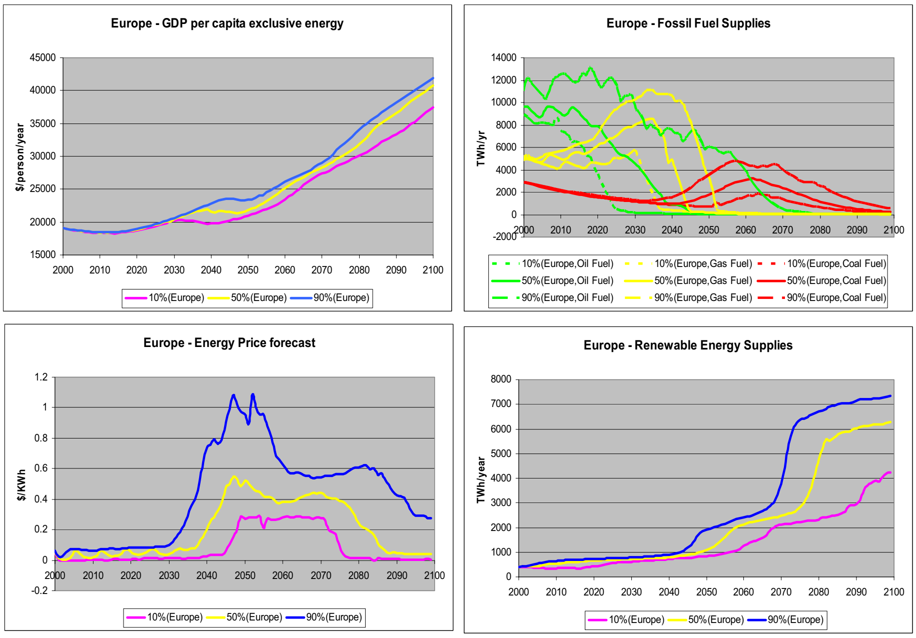


Figure 53: Total uncertainty in energy and climate

As in the FREE model by Fiddaman (1997), the CE2-model treats all generations equally (Fiddaman 1997, p 175). Future generations are likely to become much richer than current generations, and the impact of energy security and climate change on their welfare seems relatively unimportant, except for the developing world and the Asia-Pacific region where high energy import costs combined with low per capita purchasing power will reduce per capita goods consumption substantially in the first couple of decades after peak petroleum. For the developed world, the consequence is mainly a marginal reduction in per capita goods consumption due to an increased cost of energy consumption. However, the consequences of climate change on the environment in general are likely to be challenging for many European citizens.

The peak in global oil production is as illustrated in figure 54 expected to occur between 2010 and 2025, and in global gas production between 2035 and 2045. The shift in energy prices does not occur until gas production starts to decline, indicating an efficient substitution between oil and gas as the peak in oil production occurs.

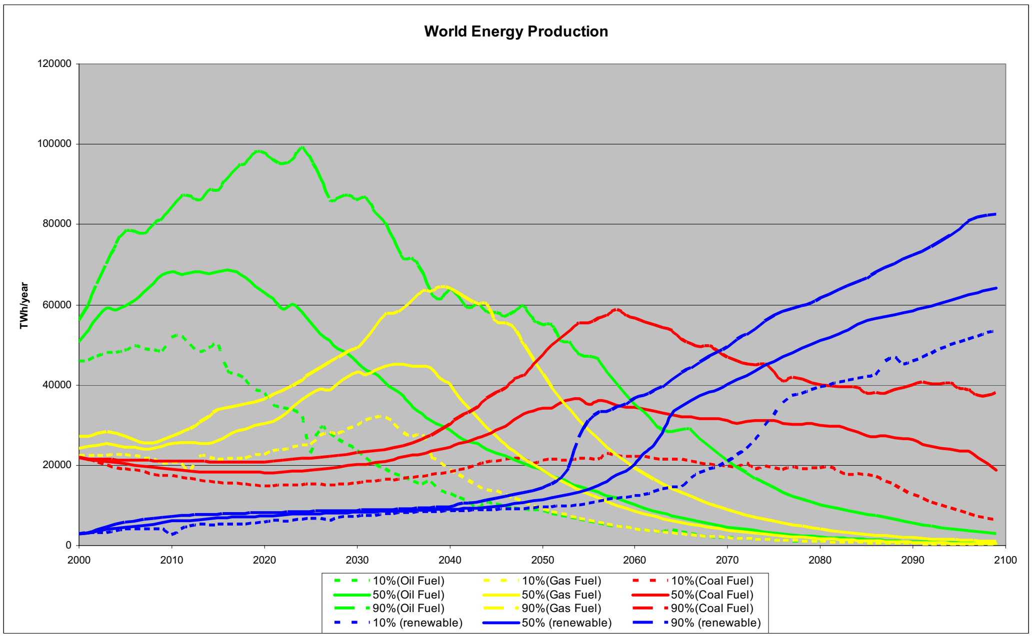


Figure 54: Modelled world energy production. Please note that this is primary energy, and that the energy losses of fossil energy supplies are 50–70 % while it is 10–20 % for renewable energy.

Without any climate policies, this study find that fossil-fuel energy will remain the dominant energy source for the next 30–50 years leading to an increase in atmospheric temperature of 1.8°C to 3.8°C towards the end of this century. This is likely to cause serious consequences for the society in future years, with substantial increases in sea level and decreased food productivity. If coal resources are larger than this work indicates, climate change will be worse than predicted here and will create severe long-term consequences due to climate change. In this century, a major challenge is the impact of a peak in fossil energy supplies, and the following disruption in energy supplies until sufficient renewable supplies are established. To avoid these consequences, which are predicted to last for a couple of decades, the world should develop energy and climate policies in order to have sufficient renewable production capacity available by 2025 when this situation might occur.

4.2 Scenario analysis

The scenarios in this thesis describe hypotheses or speculations about different paths that society can take towards the future – sustainable and non-sustainable. The scenario methodology is based on Rodrik (1999) and Shell (2005), and defines three objectives with associated driving forces located at the corners of a triangle:

Driving Force	**Objective**
Economic welfare	An open global economy
Environmental concern	Stabilisation of climate
Energy security	Sufficient and affordable energy supplies

Table 7: Driving forces in scenario development

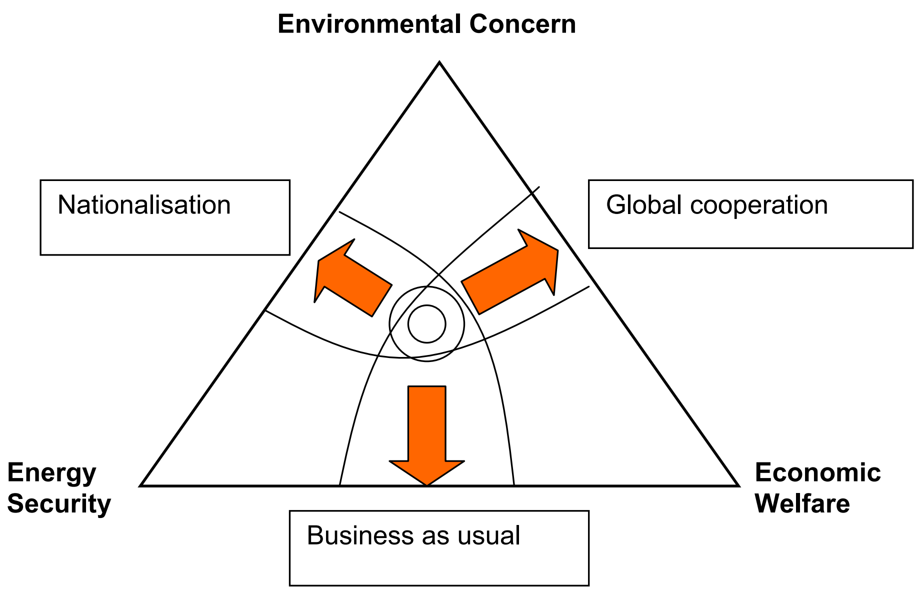


Figure 55: Trilemma triangle for scenario development

This will imply that if nations prioritise economic welfare or efficiency – nations will have to choose between environment and reliable energy supply. The most cost effective and reliable energy supply today, and in the near to medium future is fossil- based energy. There are few alternative energy sources that can compete against these fossil-based energy sources on a significant scale, especially in the transportation sector before 2030, unless governments decide to promote other energy sources through tax regimes and through support of research and development of these energy sources. Economic efficiency or an open market economy might provide energy security through the price mechanism based on a balance between supply and demand in the medium to long term. However, the open market economy based on free trade principles will lead to an energy crisis for several decades as a situation where the supply of fossil energy cannot meet demand are approached, resulting in the development of alternative energy sources. Because of the high availability of cheap oil, gas and coal, an open market will not stabilise the climate. Securing the environment in an open market will require shortages of fossil-fuel energy supply, or energy insecurity, with resulting high prices due to physical limitations or geopolitical issues.

If society prioritises to stabilise the climate, it will have to choose between economic growth and low-cost energy. Stabilising the climate will require a reduction in material consumption and emissions from the use of fossil energy sources which is unlikely in an open market that will provide cheap oil, gas and coal to the consumers far into the future. To achieve a stable climate, nations have to develop alternative energy sources and establish these in the market while at the same time restricting the physical flow of natural resources such as oil, gas and coal by government regulation.

The three basic scenarios that are described in this work are:

- Nationalisation
- Global Cooperation
- Business as Usual

The assumptions in the "Business as Usual" scenario is to a large degree similar to IEA's projections in "World Energy Outlook 2008" (2008b). The main difference between the "Business as Usual" scenario presented here and earlier works (Shell 2005; CERA 2006; IEA 2008b) is a more pessimistic view of the speed of capacity increase in the oil and gas rich regions such as the Middle East, and a more optimistic view on climate policies in Europe. The "Global Cooperation" scenario describes a development where the world emphasises community values and efficiency where the market provides solutions to the energy security within environmental constraints. In "Nationalisation", energy security and community values are emphasised at the expense of economic efficiency.

Scenarios are mainly used to imagine different ways the world could develop, and help the user to ask better questions on important issues (Schwartz 1998, p 203).

4.2.1 Policy design and uncertainty

Nordhaus and Boyer (2000) used a carbon tax of zero in all regions to define the reference case of their model to project what might happen if no government action is taken to slow global warming. In the baseline case, emissions are determined by an unregulated market (Nordhaus and Boyer 2000, p 25). The "Business as Usual" scenario as developed here is based on the same principle, but assumes a carbon tax in Europe to stabilise European CO_2 emissions, which is reinvested to subsidise investments in new renewable energy and CCS.

A Pareto-optimal climate change policy can be modelled by setting the carbon tax in each region equal to the economic impact of one unit of emissions today on the present value of consumption (Nordhaus and Boyer 2000, p 25). The weighted cost of carbon emissions using the P50 estimate of carbon costs from the CE2-model gives an undiscounted carbon cost of \$ 129 per ton in Europe by year 2100. However, sensitivities where the simulations are extended to year 2300 indicate an exponential growth in climate costs beyond year 2100. Sustainability principles should in principle apply when it comes to CO_2 emissions, where growth should be based on a principle of not reducing the welfare of future generations. This will imply a zero discount rate. The implication is that a price of CO_2 below \$ 129 per ton in Europe is likely to generate a positive value for society in the long run. This is equivalent to a climate cost of approximately \$40 per barrel of oil.

In principle, a global environmental policy could follow either an evolutionary path or a challenge and response path. Evolution could lead to an eco-disaster simply by producing more of the same, while a challenge and response path could lead to an eco-boom (Schwartz 1998, p 157-158). Sensitivities using several different carbon tax and carbon market options confirm that the most efficient approach in terms of reducing carbon dioxide emissions is to use a carbon cost, based on a tax or market price, and reinvest the revenues as subsidies for CCS or renewable energy as found by Gerlagh et al. (2006). Such a policy would lead to extensive investments in CCS and accelerated investments in renewable energy. In the scenarios developed here, this principle has been used in regions with an active climate policy. This thesis has not investigated different climate change policies in Europe or the world, but has emphasised the impact of such policies on the energy market and on business opportunities of following such policies for Norway. There are several policy options available to secure energy supplies and reduce climate impact, such as carbon tax, carbon market, legislation, emission standards, subsidies and government purchases. Unfortunately, tradeoffs between energy security, economy and the environment "have strong potential to be resolved by accepting increased environmental damage in order to avoid economic or security risks" (Farrell and Brandt 2006).

In principle, there are three climate policies in these scenarios; no climate policy, national climate policies in Norway and Europe and a global climate policy. Modelled sensitivities using the carbon price model and emission allowances show that energy prices will increase gradually as emission allowances are tightened, and decrease when the price is sufficiently high to create responses to the carbon price. Using the actual climate costs at the time the impact occurs could be a policy which is easier to argue for, but unfortunately such policies will have effect too late to reduce emissions significantly.

4.2.2 Business as usual

The "Business as Usual" scenario assumes a carbon tax of $ 90/ton in Norway and Europe. The tax revenues are reinvested as subsidies for the production of renewable energy and carbon capture and storage. The carbon tax regime gives initial subsidies of up to $ 0.6/KWh for renewable energy and $ 1500/ton for CCS capacity which declines as the emissions decline. Modelled sensitivities with higher carbon tax give low marginal decreases in emissions as illustrated in figure 56 below.

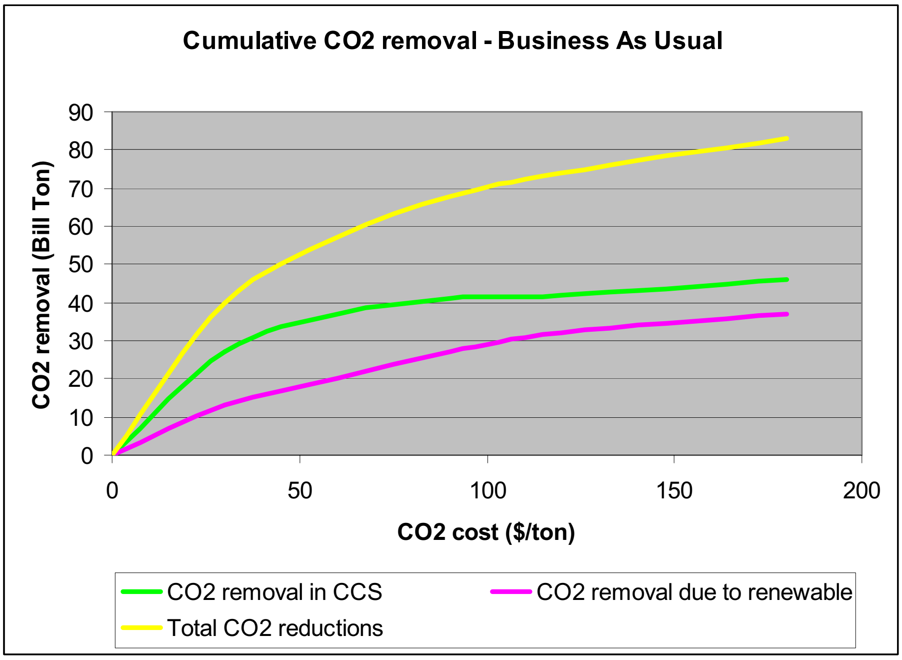


Figure 56: CO_2 removal vs CO_2 cost in Europe (Business As Usual)

The "Business as Usual" scenario assumes that CCS is available from 2015 as a commercial technology. The CCS capacity in Norway builds up to a peak capacity of approximately 40 million tons per year in 2030. Investments in CCS start in 2015 when the technology is available and reduces the Norwegian emissions to approximately 15 million tons per year. Due to the general CO_2 tax, and the breakthrough of plug-in hybrids, new vehicles are based on plug-in hybrid technology, which leads to a significant change in the transport fuel infrastructure from fossil-fuel filling stations to fossil-fuel-burning power stations. This capacity build-up will require investments of approximately $ 2 billion/year. The CO_2 level stabilises at 600 ppm, but will rise again during the next centuries due to ocean warming. This low CO_2 concentration, compared with the IPCC estimates (IPCC 2007a), is mainly caused by lower emissions from fossil fuels due to the limited resource base.

The inability to expand production capacity significantly in the oil rich regions of the world, as observed lately in OPEC nations, is assumed to continue. In the scenario, it is assumed that the fuel production capacity in North Africa, Russia and the Middle East can at maximum double within 25 years. Investments in renewable energy in Norway are based on European prices, and it is assumed that the electricity export capacity from Norway to Europe is expanded based on the revenues caused by price difference between Norway and Europe.

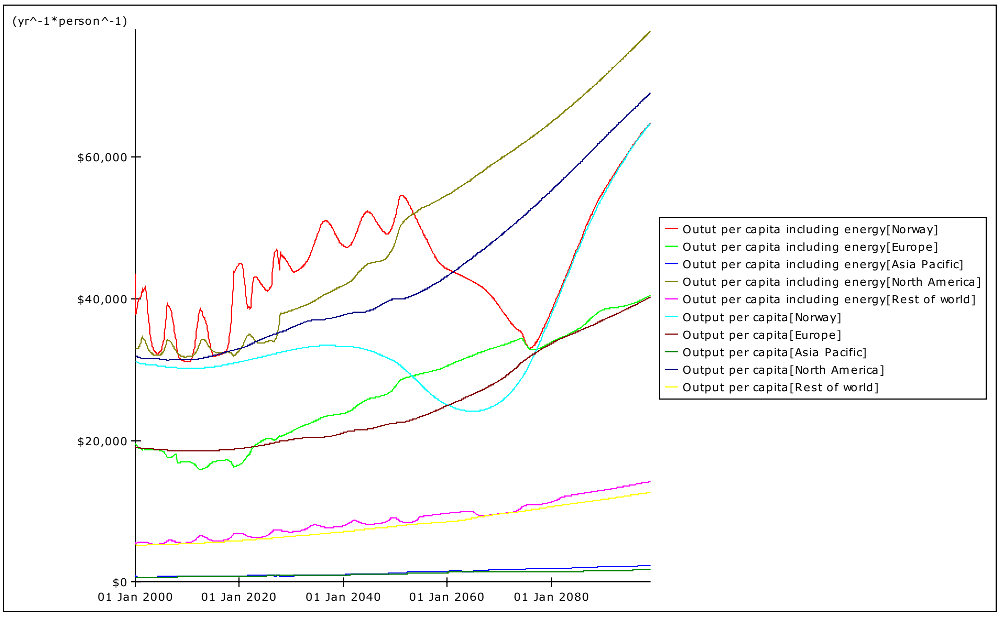


Figure 57: Output per capita with and without energy.

This leads to a significant expansion of electricity import/export capacity between Norway and Europe to 150 TWh per year. A large fraction of Norwegian resources are prioritised towards both fossil-fuel production and renewable energy production due to the high energy prices in the European market in this scenario. This leads to reduced investment in goods production, leaving Norway in a vulnerable position if energy demand and prices decreases. When the total Norwegian potential for onshore renewable energy are fully developed Europe has, in this scenario, become self sufficient due to a substantial development of offshore wind energy based on significant European renewable energy subsidies caused by reinvesting CO_2 taxes. The Norwegian energy-based value creation diminishes towards the end of the twenty-first century as illustrated in the figure 57 above because of the poor competitive position in renewable energy production.

In the “business as usual” scenario, recycling of carbon tax to renewable energy productions leads to increased investment and capacity expansion within hydro power and onshore wind in Norway, due to its cost advantages compared with offshore wind. Offshore wind in Norway remains uncompetitive compared with European projects, and does not make its way to the market.

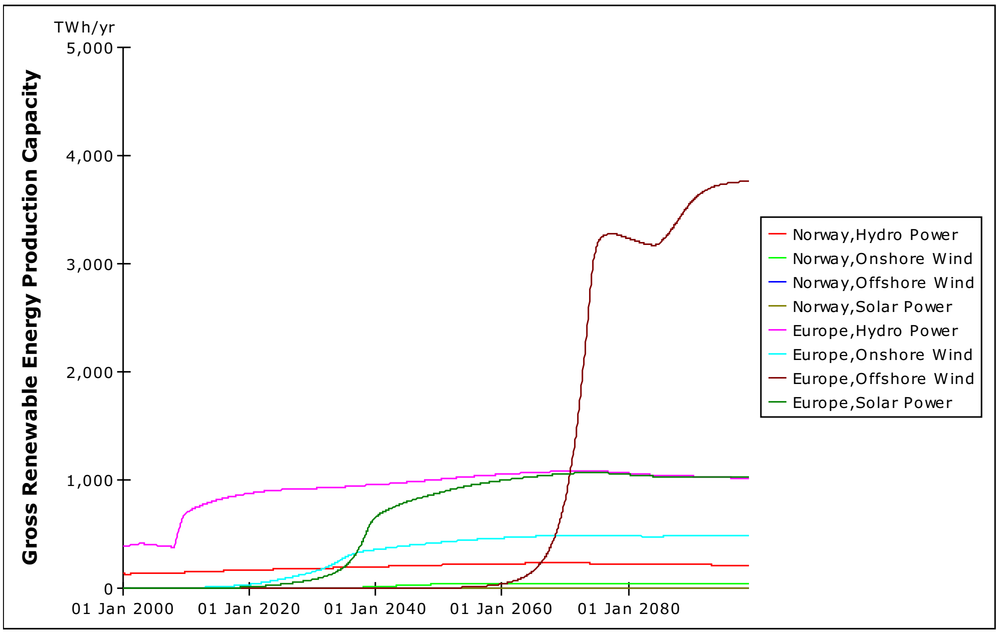


Figure 58: Renewable energy production capacity in Norway and Europe.

In the “Business as Usual” scenario, energy prices increase significantly in Europe towards 2040 and stabilise between \$ 0.3 and \$ 0.6/KWh for several decades, before declining significantly as European renewable energy sources, such as solar power and offshore wind, achieve significant cost reductions due to learning effects. In the second half of the century, renewable energy sources become dominant in the global energy market as a consequence of reduced costs and fossil fuel scarcity. Compared with Europe, coal remains an important energy source in North America, Asia-Pacific and Rest-of-world due to its importance for energy security and the lack of commercial viability for renewable energy caused by limited subsidies in these regions.

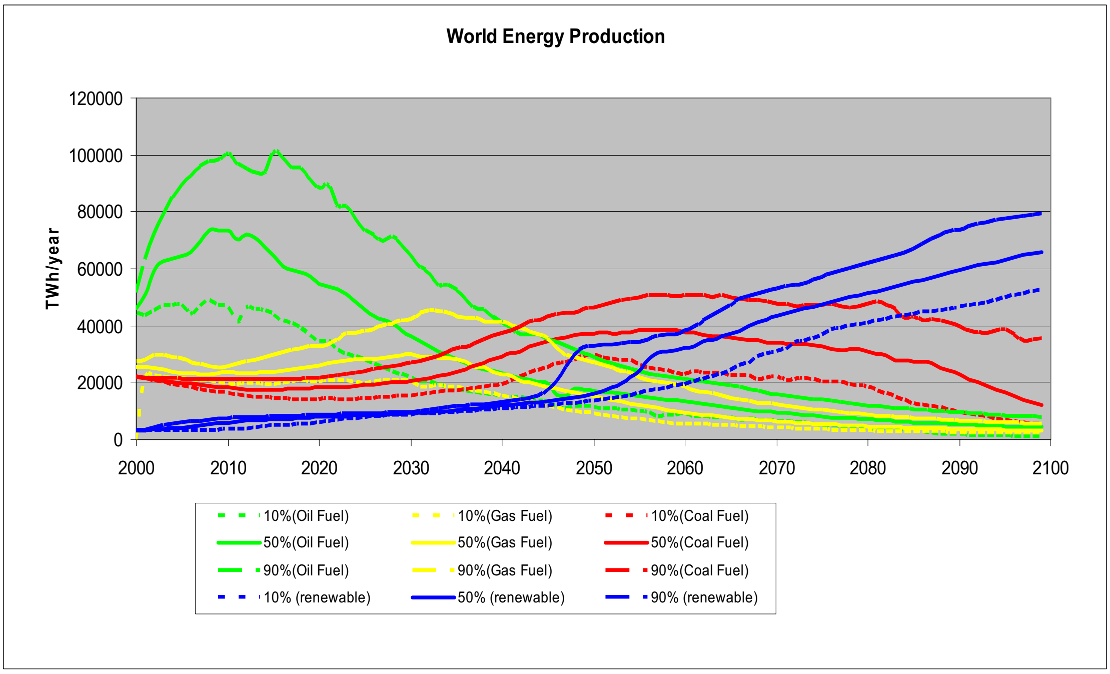


Figure 59: Global primary energy supplies in the Business as Usual scenario

It is likely that the increasing economic burden of energy caused by its reduced availability will lead the major players in the world to place a high emphasis on energy security and efficiency. The battle for energy resources between Asia and the western world will lead to growing rivalry and conflict between China and the US because energy security is considered fundamental to national security. Many nations will struggle to establish diversification of energy supply, in terms of geographical spread and energy mix, because geopolitical instability will make it difficult to invest the required amounts to secure oil and gas supply. The damages due to climate change result in costs of between 1 % and 7 % with a P50 estimate of 3 % of GDP in Europe.

4.2.3 Nationalisation

The "Nationalisation" scenario is driven by the environmental impact of local pollution and local damages. As with "Business as Usual", a CO_2 tax of $ 90 per ton is established in Europe and Norway in 2009 with the revenues recycled back to renewable energy and CCS. With increasing energy prices, the nations with the least purchasing power will lose in the competition for oil and gas supplies, and will turn to cheap coal without CCS to secure short-term growth. However, in this scenario, a CO_2 tax of $ 45 per ton is established in the Asia-Pacific region in 2030 due to increasing recognition of future climate change and an increased purchasing power which allows for higher spending on energy services. Due to an increasing awareness of the energy security challenge, there is no new investment in energy export infrastructure after 2015 because domestic energy resources are seen as a national strategic resource for further growth. Nations establish higher economic barriers to limit exposure to external threats. Conventional state-to-state relations are reinforced in the energy market and states push their own national agenda at the expense of international cooperation to secure energy supplies. Full liberalisation of energy markets is questioned by governments that try to secure long-term energy imports and secure energy diversity through support for development of domestic renewable energy sources. China in particular capitalises on its domestic market.

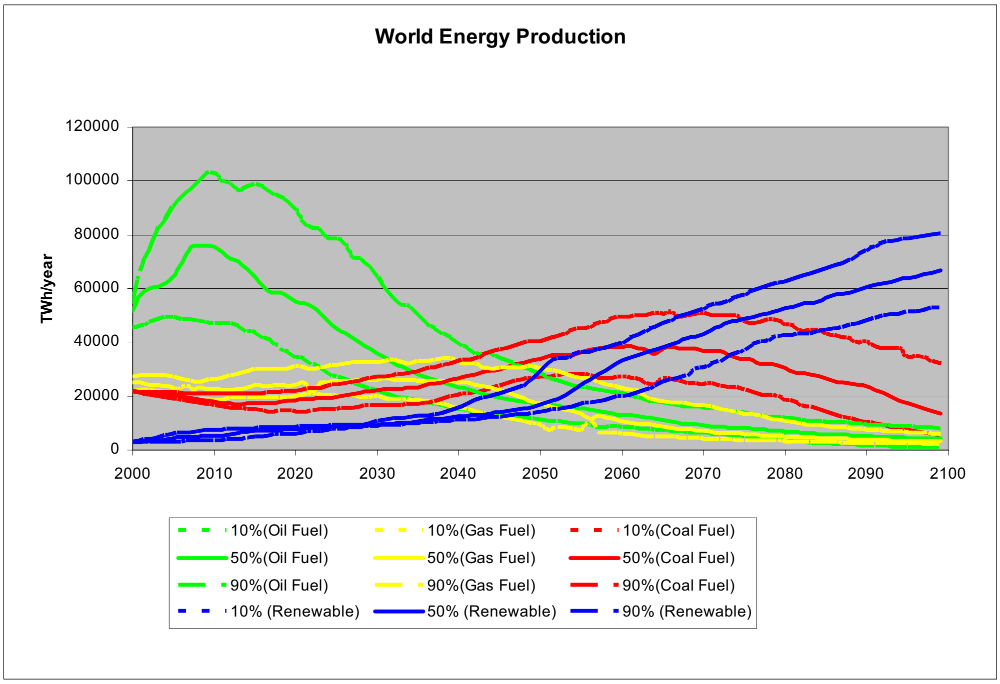


Figure 60: World energy production in the Nationalisation scenario

In the "Nationalisation" scenario, the cumulative CO_2 emissions are reduced by 273 and 204 billion tons compared with the "Reference case" and the "Business as Usual" scenario respectively, with the majority of the reduction being due to carbon capture and storage. This reduction in CO_2 emissions results in a reduction in the European climate cost of approximately 1 % of GDP in 2100 compared with the "Business as Usual" scenario with a P50 estimate of 2 %.

4.2.4 Global cooperation

The "Global cooperation" scenario assumes that a global CO_2 tax is established in 2015, and that CO_2 tax revenues are used to subsidise renewable energy and CCS. The scenario also assumes a high degree of technology transfer, where all regions of the world can utilise new achievements in energy technology due to learning in other regions. The consequence of the global CO_2 tax with recycling is a reduction of energy-related CO_2 emissions by 40 % in the period 2000 to 2100. The policies in this scenario are established as a response to the climate threat and an expected energy crisis. This is caused by a strong growth in demand for oil combined with lack of necessary investment in oil and gas import capacity due to the geopolitical uncertainty, resulting in high prices and fear of an oil peak. The market will respond to these policies and challenges by technological advances and structural changes in the energy and transportation sectors with significant public and private investment in alternative fuels, CCS and improved transportation technologies. To provide a better global environment, there is a strong regulatory co-operation between states which has strengthened cooperation within international forums and institutions. Coal technologies combined with carbon sequestration and deposition allow coal to remain a primary energy source in this scenario.

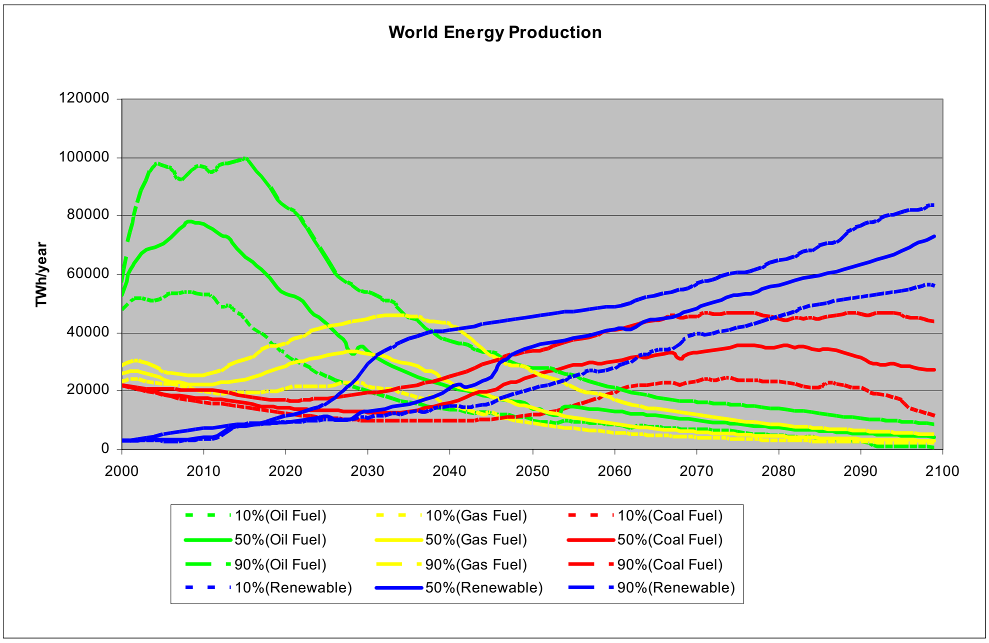


Figure 61: World energy production in the Global Cooperation scenario

4.2.5 Observations from the scenarios

Using the precautionary principle, decisions related to climate policies are in principle based on the downside expectations. The world is vulnerable to scarcity of fossil fuels and climate impact. In the reference case, reductions of 4.8 % and 2.6 % in accumulated GDP are estimated due to climate change in Europe and the world respectively. The scenarios demonstrate that a climate policy as modelled in this thesis will benefit most of the world in terms of reduced climate costs and increased long-term energy security due to accelerated development of renewable energy. The scenarios show substantial growth in renewable energy production and particularly offshore wind production in Europe. In the scenarios as modelled here, the potential for Norwegian wind power remains undeveloped because Norway does not utilise the opportunity to deliver electricity to Europe from Norwegian-based offshore wind power generation.

Scenario	Total CO_2 emissions (Billion Tons)	Energy-related CO_2 emissions (Billion	Reduction compared with reference	Reductions due to CCS (Billion Tons)	CO_2 concentration @2100 (ppm)

		Tons)	case						
				Norway	EU	Asia Pacific	North America	ROW	
Reference Case	4434	2293							675
Business As Usual	4247	2143	187	1	42				673
Nationalisation	4062	1949	372	1	44	220			661
Global cooperation	3270	1138	1164	1.3	67	367	253	174	577

Table 8: CO_2 emissions for different scenarios

The scenarios indicate that nations with substantial coal resources will, in the case of a CO_2 tax, utilise these resources in combination with CCS, while the remaining nations will expand their renewable capacity. The lift in CCS capacity in Europe and Asia-Pacific from the "Nationalisation" to "Global cooperation" scenario is mainly caused by faster learning and technology transfer between nations. The major growth in renewable energy production is basically as solar power in "Rest of World" and Asia-Pacific and as offshore wind in Europe. Figure 62 shows the developments in world renewable energy production capacity in the "Global cooperation" scenario.

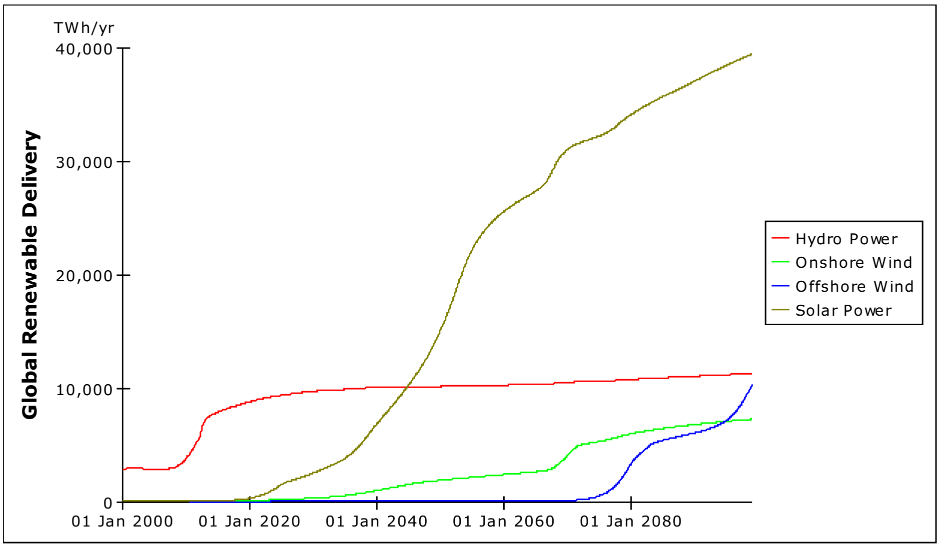


Figure 62: Renewable energy supplies in the Global Cooperation scenario

The CE2-model shows that the most efficient way to reduce emissions is by use of a CO_2 tax that is used to subsidise renewable energy and CCS. The CE2-model indicates that reinvesting this tax can make CCS viable at a relatively low tax, while a higher CO_2 tax will realise energy efficiency measures and more renewable energy, as illustrated in figure 63. Modelling of a CO_2 market and internalisation of CO_2 costs seems to be unpredictable and difficult to manage. The effect of such measures seems to be too late in time to have any significant impact on emissions.

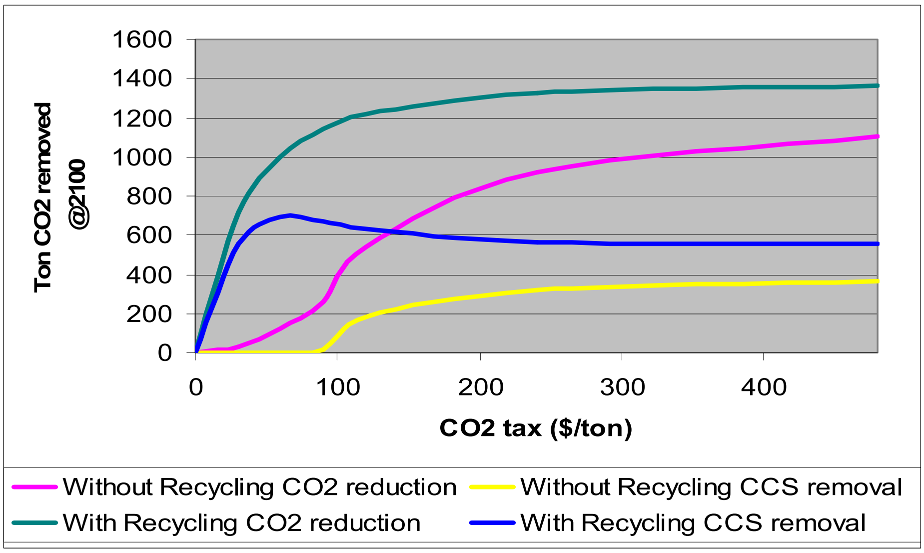


Figure 63: Effect of CO_2 tax on energy-related emissions in the Global Cooperation scenario

Energy prices are lower in "Global Cooperation" compared to the other scenarios due to a high degree of technology transfer leading to faster reductions in the costs of renewable energy and CCS. The carbon tax of \$ 90/ton is equivalent to a cost of \$ 18/MWh of fossil-based electricity, which is a relatively small fraction of future energy prices. The scenario analysis indicates that environmental policies outside of Europe will have a minor impact on the European energy market.

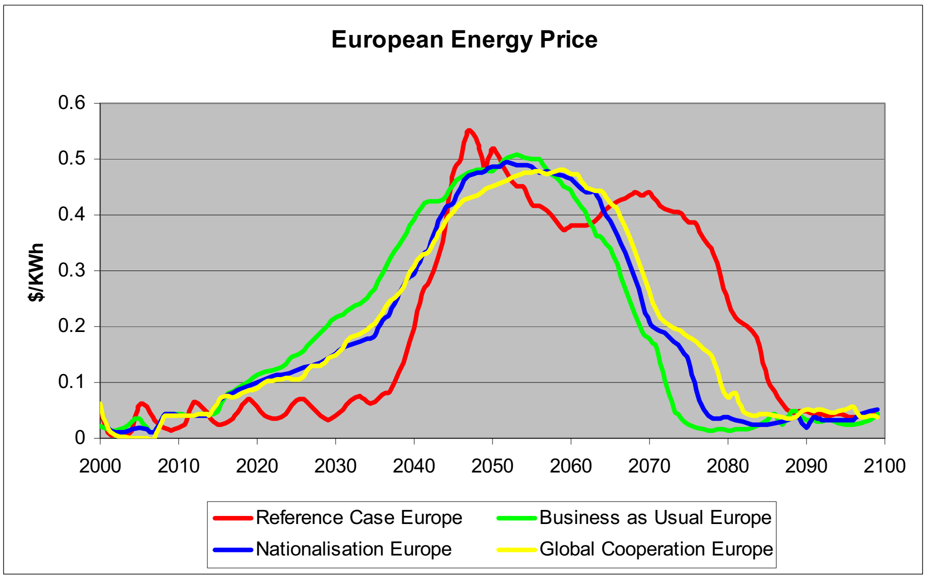


Figure 64: Development in European energy prices in different scenarios

Climate policies lead to accelerated implementation of renewable energy, and deferral of coal consumption, as illustrated in figure 65. The sensitivities show that efficient climate policies or renewable energy policies will reduce the economic shock of peak petroleum, and give a smoother transition towards a more sustainable energy system.

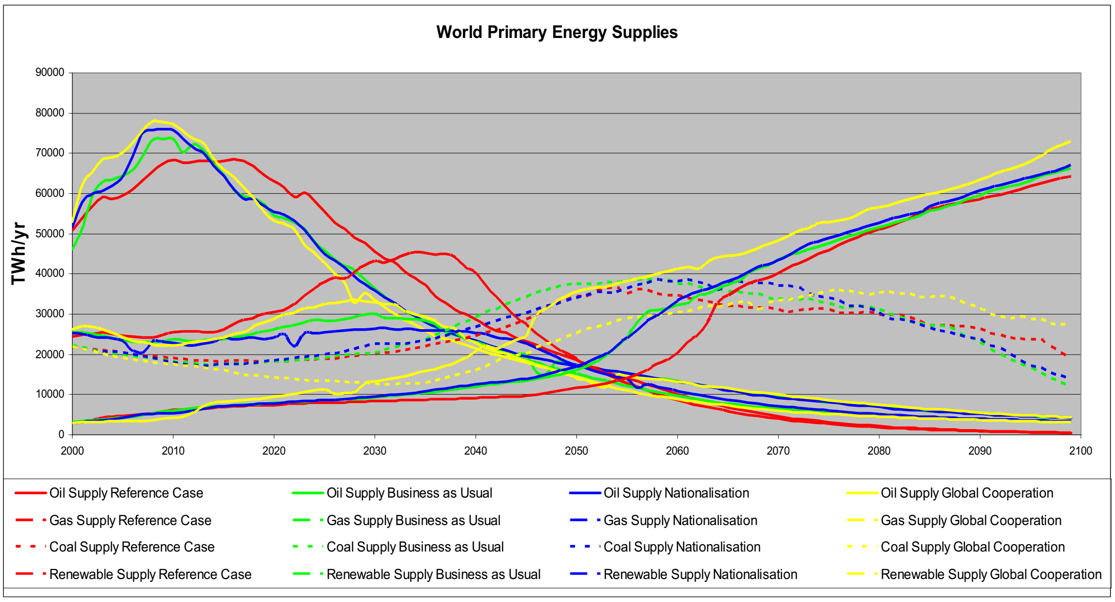


Figure 65: World primary energy supplies in different scenarios

The scenarios indicate that a policy based on the reinvestment of CO_2 tax is the most efficient policy to mitigate climate change and to reduce the impact of peak petroleum. They also indicate that an efficient climate mitigation policy should be global to be effective. The European energy market is only marginally influenced by climate policies in other regions because energy price increases caused by energy scarcity will dominate the energy market. Although the net value for the world of a climate mitigation policy is positive, it is likely to have a negative impact on Norwegian value creation in all scenarios as described above because the value of oil and gas decreases and Norway remain uncompetitive in renewable energy production. All scenarios show a significant increase in the renewable share of total energy consumption in Europe as illustrated in figure 66.

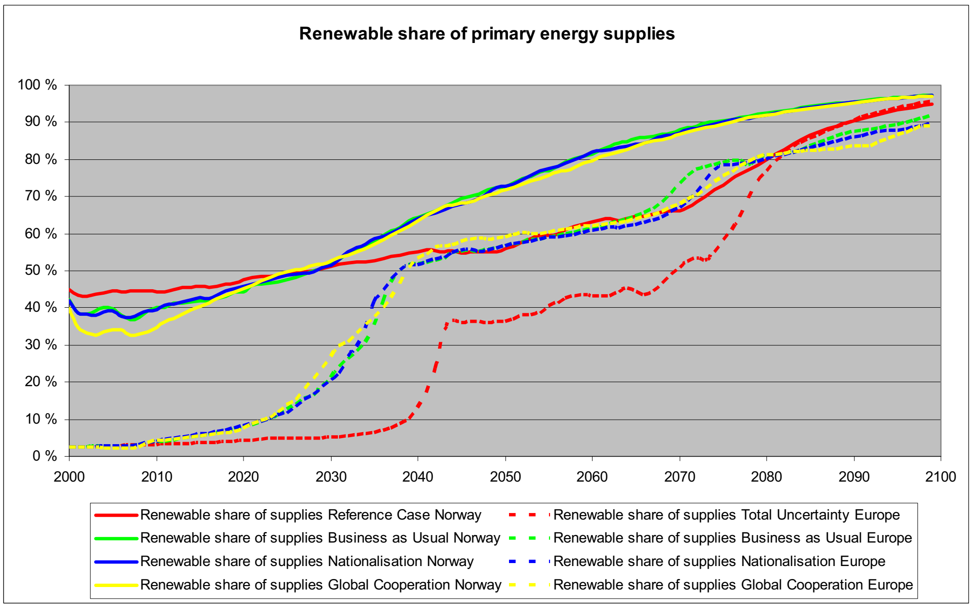


Figure 66: Renewable share of primary energy supplies in Norway and Europe for different scenarios.

4.3 Norwegian strategic position

The challenge for Norway seems to be that climate change policies will lead to reduced Norwegian value creation from fossil based energy production. On the other hand, climate policies and the European energy security situation create opportunities within renewable energy production and CCS. Norway may increase value creation by finding ways to move down the learning curve faster than its competitors in these industries. The market for renewable energy will be growing in the world, in particular for solar energy and in Europe for wind energy. However, as illustrated in the globalisation scenario, carbon capture and storage is expected to be the dominant source of emission reductions in the 21'Th century in nations with abundant coal resources such as China and North America. The Norwegian challenge is to improve Norwegian value creation in a climate mitigation policy scenario by a strategic effort using CCS or offshore wind.

The Norwegian industry is recognised for its position in offshore technology for oil and gas production and in particular subsea technologies, its ability to run large-scale projects, the highly developed energy distribution infrastructure and offshore CO_2 storage (Gotaas 2008). In Norway there is strong government support for carbon capture and storage (Stortingsmelding 2005, p 97), very limited support for renewable energy production (Stortingsmelding 2006) and limited reinvestment of CO_2 tax (Randers, Arnstad et al. 2006, p 32). The current situation in Norway may look as if the Norwegian oil industry, supported by the government, is building defences against the threat of renewable energy through strong support for the development of carbon capture and storage as the solution to the climate problem. The previous scenarios in this thesis indicate that the solution to the climate and energy challenge is relatively straightforward, not very expensive and in the long run a benefit for global and European value creation.

Reaching a global agreement on climate policies is difficult due to the diverging interests and abilities of different regions of the world (Chapter 2). It seems as the solution to the climate challenge is mainly a matter of priorities and willingness. The global oil and gas subsidies are approximately \$ 310 billion per year, which is almost equal to the required world investment in upstream oil and gas development per year to meet the growth scenario in IEA's reference case (IEA 2008b, p 38). If these subsidies were invested in CCS it would add CO_2 removal capacity of 300–500 million tons of CO_2 per year. If they were invested in wind farms, it would add an electricity production of 700 TWh per year, assuming 50 % efficiencies and a cost of \$ 2 per Watt (Mørch 2007). If the cost of military operations to secure energy supplies are added it becomes even worse (Bush 2008). It is a paradox that nations prefer to spend so much to secure and subsidise oil and gas supplies compared with what they are willing to spend on securing sustainable energy production.

The main challenge for Europe seems to be to secure energy supplies for continued economic growth in competition with Asia. A reasonable scenario would be that the nations in the former Soviet Union and the Middle East, such as Iran, Iraq, Saudi Arabia, Kazakhstan and Russia, orient their interests more towards Asia, while Europe would have to base its energy security on imports of gas from North Africa, Norway and western parts of Russia. An increased production of domestic energy within Europe should be expected, based on nuclear power and renewables. An advantage for Norway would be its geopolitical position, on the borders of the EU and closely allied with it. Norway would be a reliable energy supplier to Europe, although the share of energy supplies from Norway would be relatively low compared with the demand in a long-term perspective.

Norway is in a unique position, with large natural resources, a strong financial position, high competence in offshore CO_2 storage, offshore technology and electricity distribution. Norway has challenges with respect to market access and political priorities. On CO_2 capture, Norwegian industry seems to have experience in use of the technology but limited experience in fabrication of the process facilities.

A large-scale development of offshore wind energy would benefit from utilisation of the synergies by using Norwegian hydro power capacity as a swing producer to be able to deliver electricity according to demand in the European market. This would require a strong collaboration between several players in Norway to be able to coordinate the development of offshore wind production capacity, hydro power output, and domestic electricity distribution capacity and export capacity to the European market.

Carbon capture will have limited volume potential in Norway. The main markets seem to be in the Asia-Pacific and North America. The market in Europe can be expected to grow to approximately 500 million tons per year, requiring investments of approximately $ 2 billion per year in capacity build-up. The Norwegian industry can potentially compete on more specific parts of these facilities, and Norway can offer a storage solution in the Norwegian North Sea basin. The simulations using the CE2-

model indicate that the potential cash flow related to European carbon dioxide storage could be up to $15–25 billion per year based on a cost of $ 90 per ton of CO_2.

The Norwegian competitive position in these industries will depend on Norwegian policies to develop a competitive industry, and cooperation with Europe to develop Norwegian energy production as a reliable contributor to the European energy supply.

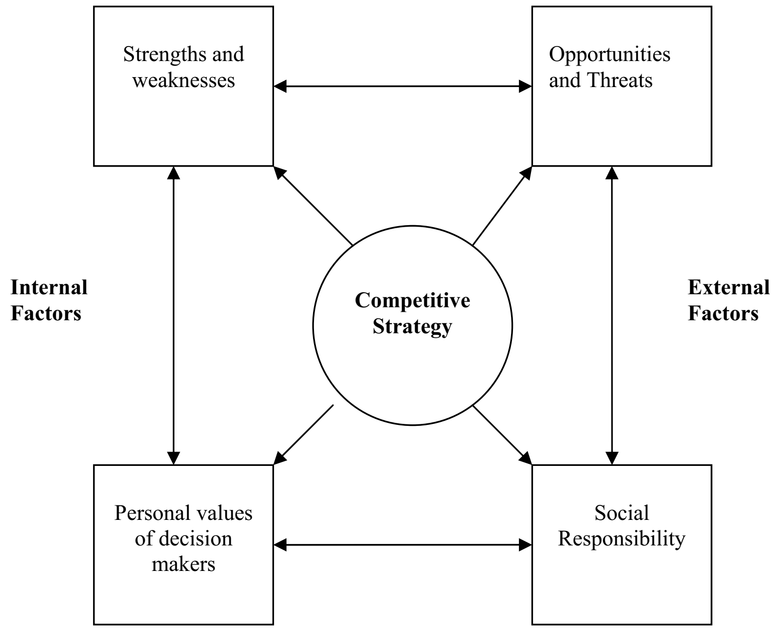


Figure 67: Porter's (1980) competitive landscape

Using Porter's (1980) model of the competitive landscape as illustrated in figure 67, the Norwegian strategic position with respect to a competitive strategy can be summarised as:

External Factors:

- Increasing challenge to secure European energy supplies due to geopolitical issues
- Increasing dependency on Russian gas in Europe
- Peak petroleum will occur within a few decades
- Europe is vulnerable with respect to climate change and is likely to take a leading position within climate mitigation policies

- European drive for diversification of supply in terms of type and origin
- Increasing competition from European industry
- Increasing energy prices in Europe
- Norwegian access to the European market and subsidies

Internal Factors:

- Leading competence on offshore and subsea development
- High competence on hydropower and electricity distribution
- Competence on offshore CO_2 storage
- Strong financial situation
- Large wind resources on the Norwegian Continental Shelf (NCS)
- Decreasing oil and gas production on NCS
- Limited capacity to develop new industry in competition with oil and gas
- Weak political willingness to develop new industries
- Short-sighted politicians – lack of vision

To develop the Norwegian position as an attractive energy supplier to the European market, a **Norwegian Competitive Strategy** should include:

- Visionary politicians with a long-term view on industrial development.
- Norway needs to develop a position as a "member" of the European energy market.
- To become a strong supplier of renewable energy to Europe will require significant investments in targeted R&D, distribution and export infrastructure, swing capacity by use of hydropower and industrial development of offshore wind.
- Develop strong commercial companies to establish a driving force in offshore wind power based on an initial high degree of government investment.
- Develop commercial solutions for CO_2 storage on the Norwegian Continental Shelf based on Norwegian offshore competence.

4.4 Norwegian strategic options

The strategic options for Norway to improve value creation compared with the scenarios that are investigated previously in this thesis are;

- Government investments in development of energy export infrastructure
- Government investments in infrastructure and offshore wind power
- Government investments in infrastructure and CCS

Based on the previous scenarios it seems likely that these solutions will not develop in Norway without strong involvement and incentives by the government, including some form of government ownership. This is necessary because of the long term perspectives and commitments that are required as well as the perceived uncertainty with respect to future energy and carbon prices, and the short-term financial focus of commercial players. To make these industries competitive, Norway needs to move down the learning curve faster than its major competitor, Europe. Without a strong policy and involvement from the Norwegian government, it is likely that Europe will move faster than Norway, attract capital and competence to European industry and eventually out-compete Norwegian industry.

4.4.1 Offshore wind energy

Offshore wind energy in Norway has an enormous energy potential, ranging from 3000 to 14000 TWh per year with an additional potential on the UK continental shelf of 3200 TWh per year (ENOVA 2007; Monbiot 2007, p 103). The current global electricity consumption is approximately 15,000 TWh per year (IEA 2007, p 92-93), which should lead to the conclusion that providing renewable energy supplies to Europe is not limited by the resource potential, but by other factors. There are a lot of risk factors such as cost, capital availability and technological maturity. However, based on the author's observations of recent experiences related to an initiative to launch a national project on offshore wind energy in Norway, the main obstacle seems to be political willingness.

The estimates in this study are based on published information from StatoilHydro ASA on the "HyWind" project (StatoilHydro 2008), an offshore wind demonstration project. An initial cost of $ 12 per Watt installed capacity is assumed, with a learning curve with 20 % improvement for each doubling of capacity. This thesis assumes a gradual increase in investments towards \$ 4 billion per year in offshore wind, which is approximately one-quarter of current investment requirements for maintaining Norwegian oil and gas production (NPD 2007).

4.4.2 Carbon capture and storage

CO_2 capture and storage technologies (CCS) can reduce CO_2 emissions from power generation, industry and the production of synthetic transport fuels by 20–28 %, allowing for continued use of fossil fuels at CO_2 prices of between \$ 50 and \$ 100/ton (Newell, Jaffe et al. 2006; IEA 2006a, p 28; Stern 2007, p 194). Since fossil-fuel power plants with CCS have higher costs and lower efficiency than traditional power plants with emissions to the atmosphere it is unlikely that any commercial firm will build one without a regulatory mandate or a price on carbon emissions (Fiddaman 2007).

The use of carbon capture and storage in Norway has been a long and winding road, with technical and political challenges (Alphen, Ruijven et al. 2009). In Norway, this started in 1992-1993, when Statoil as operator for the Sleipner West field, evaluated several field development concepts. The gas in Sleipner West contains 9 % CO_2, and the company had to reduce the CO_2 concentration to a level below 2.5 % to be able to sell the gas on the European market. Several options were evaluated, such as dilution of the gas with other sources, capturing the CO_2 at the field and then emitting the CO_2 to the atmosphere, or alternatively injecting it into a more shallow sandstone reservoir – the Utsira formation. The main reason for choosing to re-inject the CO_2 from Sleipner West into the Utsira formation was the introduction of a tax of \$55 per ton of CO_2 on emissions on the Norwegian continental shelf. This tax was introduced as an incentive for oil and gas companies to reduce their fuel consumption and the flaring of gas at their facilities. The introduction of this tax made it economically feasible to re-inject the CO_2 into the Utsira formation. The licensee decided to do this by building an offshore amine facility. The technology was well known as it was used several places for the same purpose, but not previously on these dimensions offshore. The facility demonstrated that CO_2 capture and storage could be done (Jaccard 2005, p 200-201; Alphen, Ruijven et al. 2009). Carbon capture and storage offers an opportunity to reduce carbon emissions drastically and enable many coal-rich countries to consume their coal resources within a carbon- restricted economy (Nuttall and Manz 2008).

4.5 Valuation of Norwegian strategic options

The basis for the valuation process is the "Business as Usual" scenario. This scenario includes a CO_2 tax in Europe and Norway which is reinvested to subsidise all renewable energy production and CCS based on a principle that subsidies are distributed equally per unit of zero emission energy delivery. It is assumed that CCS removes 80 % of the CO_2 emissions from fossil-fuel power stations.

Government-financed development of infrastructure

Sensitivities using the CE2-model with investments in the import/export infrastructure between Norway and Europe show an increase in hydropower and onshore wind production in Norway for export to Europe. This contributes to increased value creation in Norway in the first half of the twenty-first century. Significant production of energy in Norway will require some form of government financing of energy infrastructure to capitalise on the investments because price differentials will be insufficient and unreliable to lift a commercial investment in infrastructure.

Government-financed development of infrastructure and offshore wind power

In this scenario, dedicated financial support from the government to offshore wind power of $ 2 billion per year and an additional $ 1 billion per year in infrastructure development to lift offshore wind power into a commercial industry is modelled. These investments represent approximately twice the Norwegian carbon tax revenue for the year 2000. The impact of government support is significant. However, sensitivities with less direct financial support show similar but slower effect. Government financial support will attract financial investors and accelerate the development of offshore wind power.

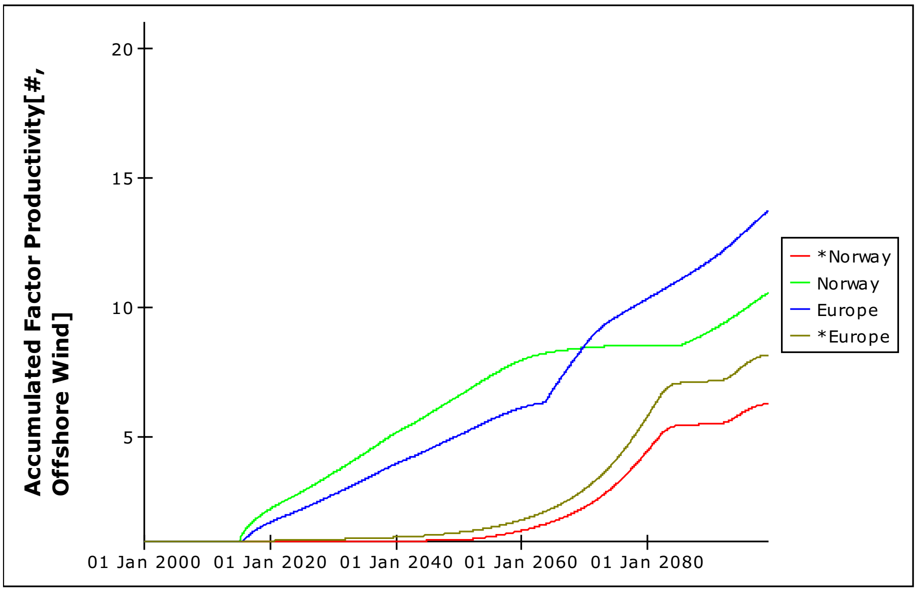


Figure 68: Accumulated learning effect for offshore wind in Norway and Europe

Dedicated financial support for offshore wind power in Norway will have a significant effect on the learning curve, and move the technology from being less attractive than the onshore renewable energies to being more attractive and cost efficient. In the "Business as Usual" scenario (red and brown curve), the Norwegian offshore wind industry is less efficient than the European industry because of higher European subsidies and support than in Norway. In a scenario where the Norwegian government invests in offshore wind power (green and blue line), Norway becomes a leader in the market due to the high domestic resource potential and development. As figure 68 above also illustrates, government investments in offshore wind power in Norway will accelerate learning and the implementation of offshore wind power in Europe due to technology transfer, and further enhancing the market for offshore wind power. As figure 69 below illustrates, substantial export of energy from Norway to Europe will have a significant impact on European energy prices and benefit both Norway and Europe.

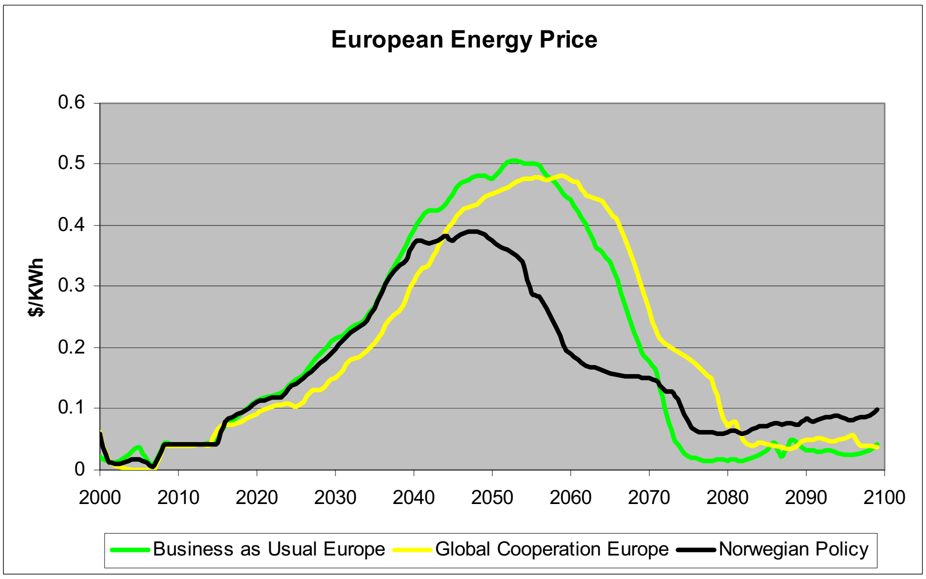


Figure 69: P50 Energy Price in Europe at different scenarios

The scenario modelling in this thesis indicates that the potential value of the offshore wind resources on the Norwegian Continental Shelf is comparable to the value of the oil and gas industry at current prices, and significantly higher at the P50 price estimate from Monte Carlo simulations using the CE2-model as illustrated in figure 70 below. However, the value is unlikely to be realised without strong governmental support and investments. Because the technologies are currently non-commercial, government investment is a key factor to initiate learning in offshore wind power to create and develop competitive advantages. Europe will out-compete Norway without sufficient financing by the Norwegian government. Sensitivities using the CE2-model indicate that direct investments in specific renewable industries are a more efficient tool to achieve competitive advantages than general subsidies for renewable energy. The CE2-model show that a general subsidy on renewable energy flows toward existing commercial technologies and not to marginal projects requiring subsidies to be realised.

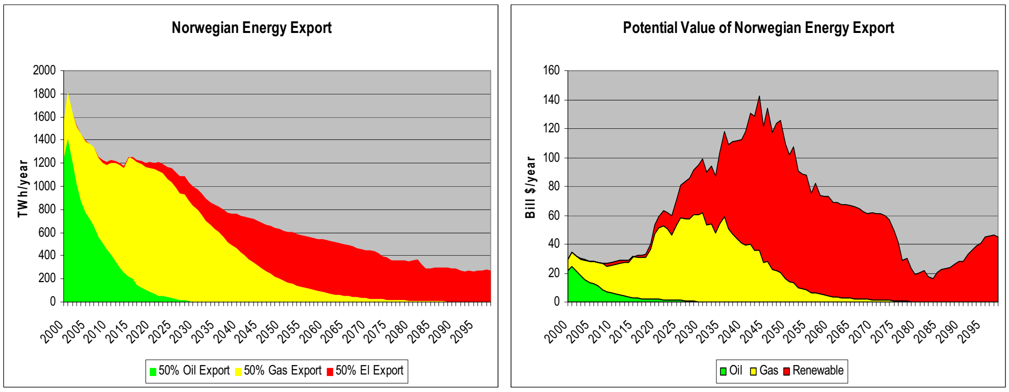


Figure 70: Modelled future energy production and value creation from the Norwegian Continental Shelf

The sensitivity for offshore wind based on the "Business as usual" scenario assumes utilisation of up to 300 TWh/year of the Norwegian offshore wind potential and increases the accumulated Norwegian GDP by 11 % as illustrated in figure 71.

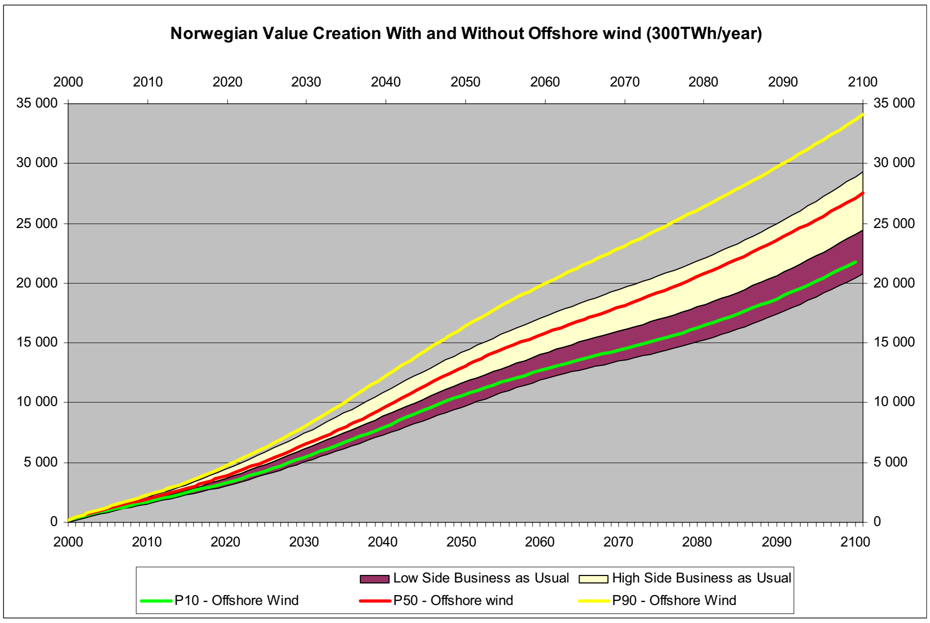


Figure 71: Norwegian value creation with and without accelerated offshore wind development

Worldwide, the accelerated technology development initiated by Norway will contribute to a reduction in CO_2 emissions of 22 billion tons by the year 2100 which is approximately five times the total Norwegian carbon dioxide emissions for the same period of time. A major contributor to the value creation from Norwegian electricity production is increasing electricity prices in Europe.

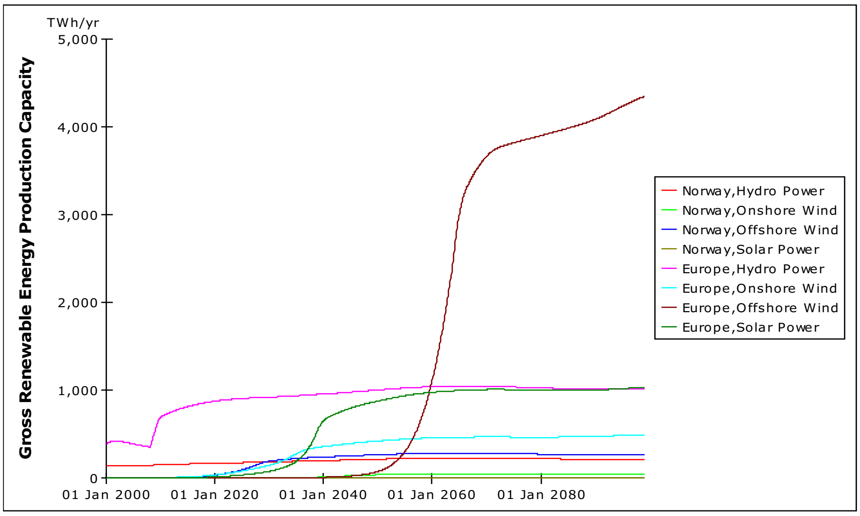


Figure 72: Renewable energy production in Norway and Europe with an aggressive Norwegian policy

Assuming a development with initial investments of \$ 4 billion per year at an investment cost of \$ 12/W, as in the "Hywind" project (StatoilHydro 2008), and a 20 % learning rate for each doubling of capacity, the offshore wind industry will be profitable at a 6 % discount rate with current European electricity prices of 56 €/MWh or \$ 0.09/KWh (Nordpool 2008). Using P50 prices from the CE2 modelled policy scenario and an expansion of offshore wind capacity towards 300 TWh per year, the cash flow from the Norwegian Continental Shelf could be maintained and increased beyond the oil and gas era as illustrated in figure 73. This would generate a pre-tax profit of \$ 60 billion at a 7 % discount rate and an undiscounted pre-tax profit of \$1000 billion in the next 50 years.

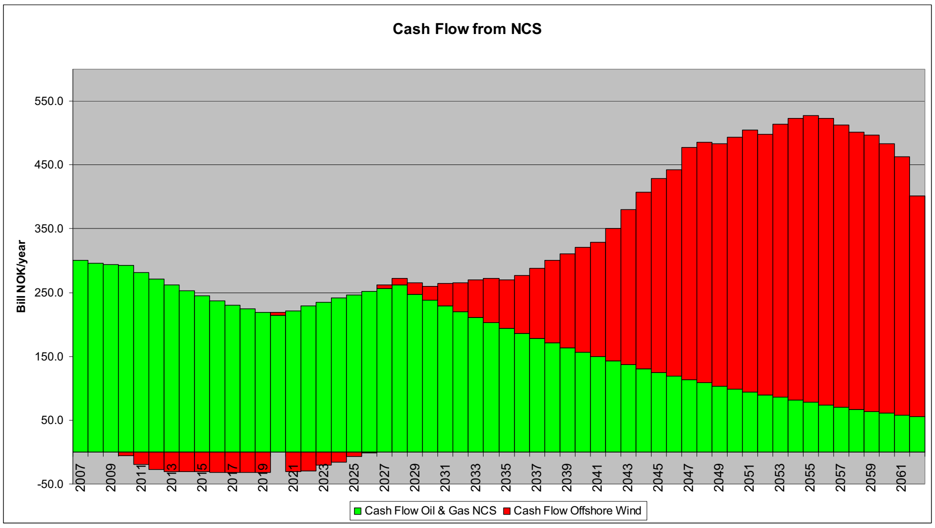


Figure 73: Value creation from the Norwegian Continental Shelf with a more moderate development

Finally, the CE2-model shows that the value of a Norwegian offshore wind development will increase if there is no CO_2 tax in Europe. This is due to delayed implementation of offshore wind power in Europe, which again will improve the Norwegian competitive position.

Government-financed development of infrastructure and CCS

A policy with direct government investments in CCS will accelerate implementation of CCS in Norway compared with the Business as Usual scenario where CCS will contribute to reductions in Norwegian CO_2 emissions as illustrated in figure 74. However, sensitivities show that government investments in CCS will delay development of offshore wind power because competition for limited resources will slow down the learning effect in offshore wind.

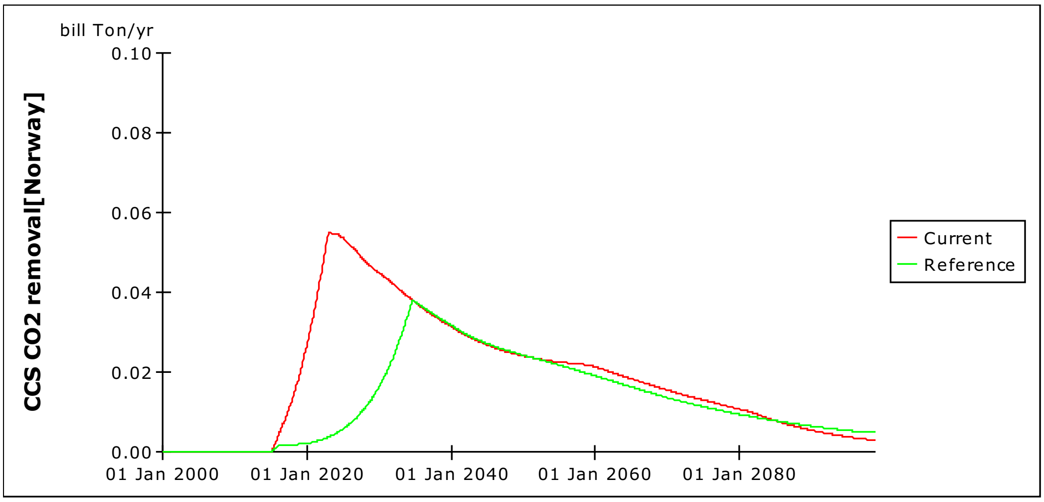


Figure 74: CO_2 removal in CCS in Norway for Business as Usual (green), and a sensitivity with direct government investments in CCS from 2015 (red).

For CCS, it seems difficult to create any significant value in Norway, although the technology may be important to reduce future CO_2 emissions globally, particularly in coal-rich nations. By use of government investments and incentives, Norway may achieve a leading position within this industry. However, due to the limited use in the domestic market, maintaining this position over time will be difficult when other nations apply the technology in their own domestic market. CCS will be a significant industry, where Norway can take a position as a technology provider, but it is probably easier to maintain a strong position within an industry where Norway can apply the technology domestically. Carbon storage might be a growing industry with a total undiscounted turnover in Europe of $ 1500 billion in this century assuming that one third of the CO_2 cost is related to storage. However, since a carbon market or tax will be a cost to society in a short-term perspective, although it is a benefit in the long-term perspective, it is unlikely that this industry will become a very attractive one in Norway as taxes would have to be as low as possible.

4.6 Closing the Norwegian value creation gap

CCS has the potential to remove approximately 2 billion tons of CO_2 emissions in Norway and 1000 billion tons worldwide by the end of the century at a relatively low cost. A global CO_2 tax of $ 40–90/ton seems sufficient to realise this reduction if the tax applies to all emissions and is reinvested to subsidise renewable energy production and CCS. Due to the limited domestic market, CCS is a technology where it is unlikely that Norway can maintain a leading position to create value in Norway, although Norwegian companies might become leaders in the international CCS market. As figure 75 illustrates, there is a large potential for value creation in offshore wind power, if Norway succeeds in establishing competitive advantages within this industry, based on a significant domestic resource base. To become a successful business, CCS depends on a carbon price being charged. Renewable energy may become competitive either if a carbon price is introduced or if the margins improve due to higher energy prices or lower costs. CCS might be an important technology to allow for the continued use of fossil fuel without severe negative climate impact. It is as illustrated in figure 75 difficult to see that CCS can play a significant role in future value creation for Norway. Offshore wind power, however, has the potential to become a major industry in Norway comparable to the current oil and gas industry.

Norwegian Energy and Climate Policy

Decicions	Undiscounted Net Value Creation relative to Business as Usual	Percent change relative to Business as Usual
	Bill $	
Business As Usual	0	0.00 %
Government Investment in infrastructure only	-344	-1.51 %
Government investment in offshore wind (300 TWh/yr) and infrastructure	2529	11.12 %
Government investment in CCS and infrastructure	-269	-1.18 %

Figure 75: Norwegian Value Creation (Accumulated GDP at year 2100) in different scenarios

Government investments in the Norwegian offshore wind industry can contribute to creation of a significant business in Norway due to accelerated learning and technology implementation, and also accelerate the implementation of the technology in Europe. This will create a large market in Norway and triple the European market for offshore wind power in the period up to 2100 compared with the Business as Usual scenario.

The case of offshore wind demonstrates that an active policy in Norway to develop a new renewable energy business can change the path of the energy system in Europe and the world, towards a renewable path at acceptable costs. Such policies will be beneficial for Norway and Europe in terms of value creation, energy security and climate mitigation.

Norway is in an excellent position to help to solve the climate and energy challenges for Europe. Norway may use the current focus on climate change to prioritise capital and resources towards renewable energy production. Specifically, Norway could develop a combination of offshore wind and hydro power to a substantial export commodity, providing energy security to Europe while generating a more climate-friendly energy supply. For Norwegian value creation, it is essential to develop offshore wind into an energy source that is competitive with solar and coal before the petroleum peak occurs with an associated rise in energy prices. Otherwise, path dependence due to infrastructure investments will create lock-ins in the energy system, where customers and investors will build on infrastructure and facilities developed by the early winners to provide new energy supplies, such as coal.

This study finds that the value of a Norwegian offshore wind development will decrease as illustrated in figure 76 as the climate changes increase, due to increasing capital costs in Europe. This cost increase lead to reductions in the European energy demand and European energy prices. To secure future value creation from a Norwegian offshore wind-power industry, it is in Norway’s interest to limit the climate change as much as possible.

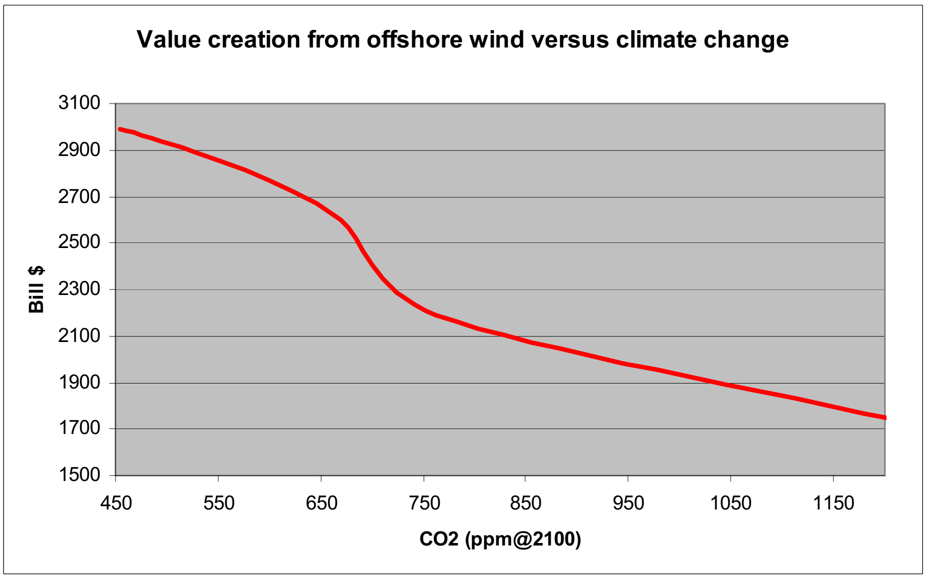


Figure 76: Estimated value of Norwegian offshore wind versus CO_2 concentration in year 2100.

The value creation based on Norwegian offshore wind power can increase further if the energy is used for industrial production in Norway. Norway has a strong position within metallurgical industries based on its earlier industrial development, experience and competence. An option could be to produce silicon for solar cells in Norway for export to southern Europe and North Africa, where its use would produce approximately 30 times more electricity than would be used in the production process (Jungbluth, Tuchschmid et al. 2008). Using the energy for industrial production in Norway will increase the Norwegian value creation significantly compared with export of pure electricity to Europe.

5 Discussion

The world will change fundamentally with respect to energy and energy security in the next few decades. A new energy paradigm is required to understand and cope with these changes. Traditional economic analysis may be insufficient to explain future changes in the energy market due to feedback loops and delays in the overall system as described in chapter 3.3. The future energy prices will probably be far outside the range of historical experience where use of current elasticity of demand, supply and substitution will not hold in evaluations of the future energy system. This chapter discuss the results described in chapter 4 based on the theoretical background in chapter 2 and the hypothesis as described in chapter 1.

5.1 Modelling of a complex world

Modelling the complexity of the real world requires an approach where problems are addressed and articulated in order to solve the problem without modelling the energy-economy-environment system in detail (Sterman 2000, p 89-90). Problem articulation has been difficult in this context. The process in itself has been a valuable learning process where issues have been looked into, modelled and removed because they proved to be less important in the overall context. The CE2-model is complex, but the modelling process has created increased knowledge and understanding of the complex feedback processes in the real world. The modelling process can be illustrated by figure 77, where the process changes the modeller’s view of the real world as the real world data gives important feedback to the modelling process.

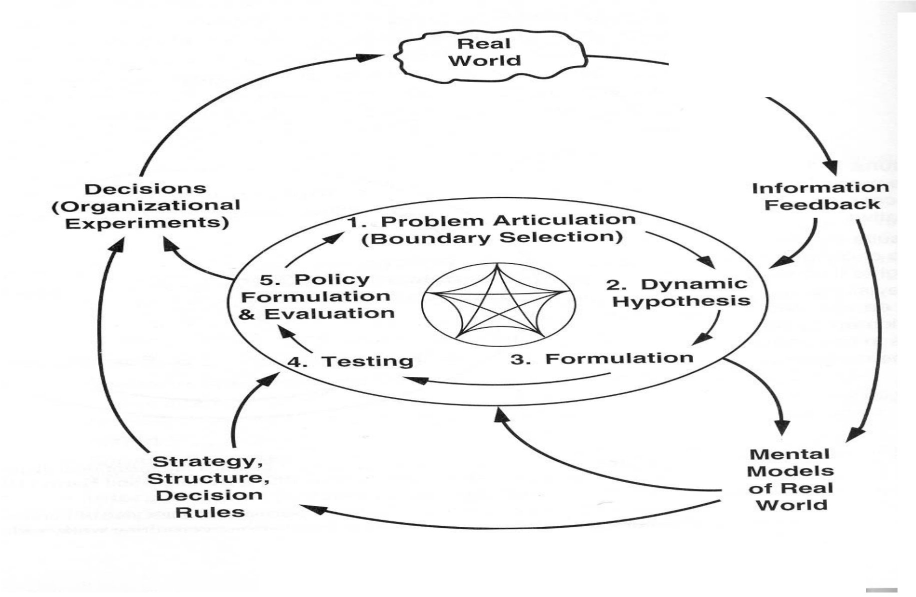


Figure 77: Modelling the real world (Sterman 2000)

It is unlikely that the global energy-economy-environment system can sustain unlimited exponential growth for a long period of time (Sterman 2000, p 118-121). The growth may decline within the relatively near future and stabilise as a response to energy resource constraints or overshoot and collapse as a consequence of environmental limits.

5.2 Path dependence and lock-ins

Energy and climate policies are sensitive to lock-ins and path dependency because companies often find it more profitable to invest in technologies that are already competitive as described in chapter 2.6. Currently the energy system seems locked-in to a fossil fuel consuming path due to historical developments and positive feedback mechanisms such as cost efficiency, economies of scale, fuel flexibility and a capital stock that reinforces the current position. A new technology requiring a different infrastructure than the existing one will have a considerable competitive disadvantage even if it offers significantly improved performance, creating path dependence. New technologies that can use existing infrastructure will usually be adopted more rapidly in the market. Many innovations will never reach commercialisation even though they are potentially superior to established alternatives (Grubb, Köhler et al. 2002; Löschel 2002). It is a dilemma that new sustainable technology is forced to compete on the global market with existing cost-optimised technology, which makes it extremely difficult to achieve change (Gether 2004, p 193). This lock-in process makes it unlikely that traditional measures such as carbon tax or emission rights will be sufficient to bring about the necessary changes in the energy system due to structural barriers such as the infrastructure development (Maréchal 2007).

IEA (2006a) found that a co-ordinated international effort is required to achieve significant reductions in CO_2 emissions. Strong co-operation will be needed between the developed and developing nations, and between industry and governments. This must be carried out before a new generation of inefficient and high-carbon energy infrastructure is locked into place (IEA 2006a, p 31). For instance, in the car manufacturing industry, a great deal of effort has been put into maintaining the existing petroleum-based transport system. This has included the “Hydrogen blinding”, where the belief in hydrogen-based technology has effectively drained the R&D efforts away from developing electrical cars, even though it is well known that hydrogen-based technologies are less energy efficient than battery- based technologies (Paine 2007). In Norway, it seems as the nation experience the same phenomenon, a “CCS blinding” where the R&D efforts on CCS drain the resources available for research on renewable energy sources.

The energy systems are locked into fossil fuels which strengthen their position every day as new infrastructure based on fossil fuels is developed. A shift towards a sustainable path will require strong forces in order to initiate the jump away from the established system towards a new and sustainable solution.

5.3 The climate challenge

As shown in chapter 2.4, historic climate change has been driven mainly by changes in insolation, where changes in the atmospheric CO_2 concentration is a consequence rather than the cause of climate change. CO_2 is a greenhouse gas that will lead to increasing atmospheric temperature if the CO_2 concentration increases. As the atmospheric temperature increases the ocean temperature will increase and the CO_2 equilibrium between ocean and atmosphere will shift towards the atmosphere.

Atmospheric temperature will increase as a consequence of increased CO_2 concentration, probably 3°C for each doubling of CO_2 concentration (IPCC 2007a, p

66). The ocean will most likely change from being a carbon sink to a carbon source as it gradually heats due to heat flux from the atmosphere (Cox, Betts et al. 2000). A 3°C warming is expected to be enough to melt the Greenland ice sheet, causing an increase in sea level by up to 7 metres (Archer 2007, p 153). The uncertainty related to the carbon cycle and the temperature effect of increasing CO_2 concentration is large. Today, the main uncertainty in climate modelling is related to clouds, because clouds cool the planet by reflecting visible light, but water vapour also warms the planet by absorbing infrared light (IPCC 2007a, p 635). The carbon flux from the ocean to the atmosphere increases in strength as the ocean temperature increases and makes it increasingly more difficult to achieve stabilisation of the CO_2 concentration in the atmosphere.

The climate will change due to increasing CO_2 concentration in the atmosphere, but there is still uncertainty with respect to the speed and magnitude of these changes. Even if it seems difficult to stabilise climate today, achieving stabilisation of CO_2 concentrations to save the planet is a lot easier now than it will be later as the climate mitigation measures today do not have to compensate as much for the increased flux from ocean to atmosphere as in the future.

5.4 The energy security challenge

The world will experience that it becomes increasingly more difficult and expensive to maintain the current high production levels of oil and gas. The world will be more dependent on limited oil and gas supplies from a limited number of geopolitical unstable locations. This will result in increases in energy prices. These energy price increases may again lead to an economic recession as energy costs increases its share of total production costs. The economic recession may be reduced or avoided through the development of renewable energy production, nuclear or coal power to allow for a smooth transition to other energy sources. Nuclear fuel resources are, however, insufficient to provide stable energy supplies for a long time. Coal power is not sustainable, and its use will lead to severe environmental problems. To become sustainable, society would have to turn to renewable energy sources. Biomass as a large scale energy source seems to be challenging in terms of competition towards food production. Other renewable energy sources, such as solar and wind power, could provide almost unlimited amounts of electric power to the world.

It will be necessary to develop cheaper and more attractive renewable energy resources in order to keep fossil fuels in the ground. This is mainly an issue of how rapidly the marginal cost of renewable energy can decrease and how rapidly the marginal cost of non-renewable energy will increase. Policies to decrease the cost of renewable energy will involve R&D, subsidies and taxation of CO_2 emissions and fossil-fuel energy sources. If nations are unable to keep fossil resources in the ground, the world has to find ways to capture and remove CO_2 from the atmosphere to avoid severe climate changes.

The issues of energy security, energy resources and the environmental implications of energy use receive increasing attention in the society (IEA 2006b; Stern 2007; IPCC 2007a; IEA 2008a; IEA 2008b). It is increasingly acknowledged that energy supplies are important to economic growth and development, and that the environmental consequences of energy use will cause an increasing economic burden for the society.

> The world is facing twin energy-related threats: that of not having adequate and secure supplies of energy at affordable prices and that of environmental harm caused by consuming too much of it (IEA 2006b, p 37).

As seen in chapter 2.1.1, the global economy seems to move from a situation far from ecological limits (weak sustainability position) to a situation where the economy is restricted by these limits (strong sustainability position), resulting in a reduced flow of materials from the environment to the economy with increasing prices of materials – such as fossil fuels. Neoclassical economic theory does not include the flow of materials and energy into the economy, but assume that economic growth can be explained entirely by technological progress, capital and labour (Solow 2000). In the last decades, endogenous growth theories have been developed to explain how technological progress develops in the economy (Aghion and Howitt 1998; Barro 2004). These models are useful to understand and model how R&D and human capital contributes to economic growth. Ayres (Ayres and Warr 2005) showed that the technological progress in the USA is linked to the development in useful energy –

“exergy; and demonstrated that energy could replace technological progress in the growth equation. The approach used in this thesis assumes that all physical capital requires energy to be productive, that energy and capital are complements, and estimates an operating capital based on the fraction of required energy that is supplied by the energy system as shown in chapter 2.2.2 and 2.2.3.

Europe imports approximately 50 % of its current energy consumption, mainly as fossil fuels from Russia, Norway, North Africa and the Middle East. Energy imports are expected to increase in the years to come and thus increase European dependency on fossil fuels from geopolitical unstable areas. As the resources become scarcer, and an increasing fraction of the energy import comes from these geopolitical unstable regions, the geopolitical tension should be expected to increase. Securing energy supplies for a growing European economy will be increasingly more important and difficult in the future. The sustainability paradigm will gradually move from a weak sustainability position to a strong sustainability position.

5.5 Future greenhouse gas emissions

The energy-related greenhouse gas emissions in the scenarios in this thesis are significantly lower than estimates by IPCC (2007a, p 803) as illustrated in figure 78. The CE2-model estimates that atmospheric CO_2 will stabilise at approximately 450 ppm in the Business as Usual scenario if there were no non-energy greenhouse gas emissions. However, non-energy-related greenhouse gas emissions will increase as the economy grows and are likely to become the major source of greenhouse gas emissions toward the end of the century due to a decreasing energy share of total CO_2 emissions.

Reproducing the IPCC (2007a, p 803) emissions scenarios would require fossil fuel resources four times higher than the estimated resources used in this thesis. This would according to the CE2-model lead to an atmospheric CO_2 concentration of 900 ppm in year 2100. Based on this study, it seems as IPCC (2007a) overestimate future energy-related CO_2 emissions. There is, however, significant uncertainty related to coal and unconventional oil resources. The precautionary principle should lead to a proactive approach in terms of climate mitigation.

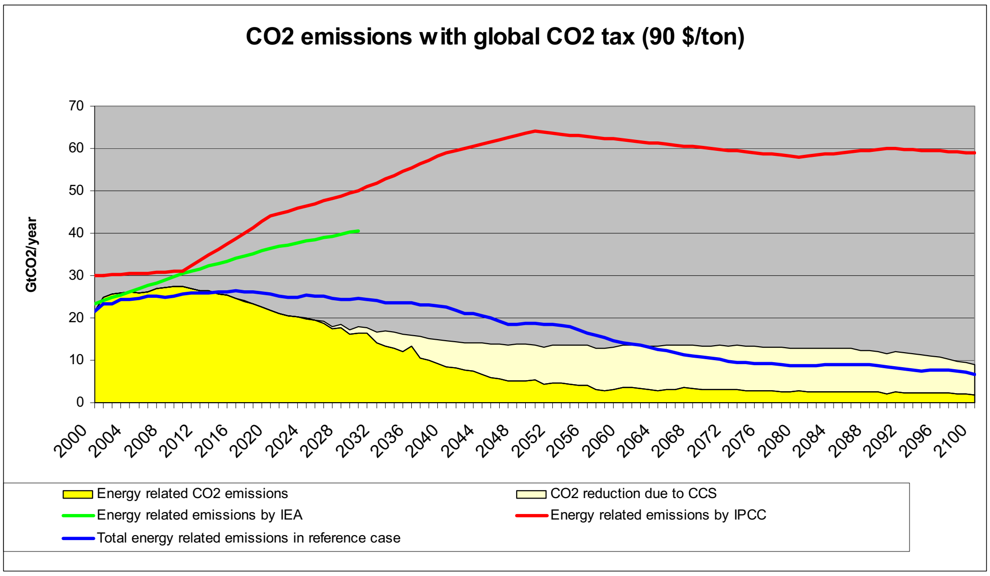


Figure 78: Energy-related CO2 emissions in the global cooperation scenario, compared with IPCC and IEA estimates.

The climate threat should lead to an increased attention on sustainable development. To avoid compromising the ability of future generations to meet their needs, society has to treat the environment as something that is intended to last forever. This should lead decision makers to use a zero discount factor for environmental projects (Solow 2000, p 83; Stern 2007, p 59-60). Using a zero discount rate, and climate costs based on IPCC (2007a) and Nordhaus and Boyer (2000), this study finds that the accumulated European cost of carbon dioxide emissions are $ 129 per ton by the end of this century. This is equivalent to a climate cost of $40 per barrel of oil, more than the historical cost of oil. It should be noticed that the cost of climate change, using the CE2-model, is predicted to continue to increase exponentially into the future. Using a cost of CO_2 emissions of up to $ 129 per ton in Europe can therefore be justified.

The scenario analyses show that a global climate policy on CO_2 emissions can reduce energy-related CO_2 emissions by up to 50 % in this century. The scenarios also indicate that national and regional approaches are less efficient than global cooperation in terms of reductions in CO_2 emissions, and that a reinvestment of carbon tax in renewable energy services and CCS is approximately five times more efficient than a carbon tax alone. The scenarios show that international cooperation and transfer of new technology is important to achieve large reductions in CO_2 emissions.

5.6 Global policies for sustainability

The climate risk and energy security situations of different nations and regions of the world based on the findings in this thesis are summed up in figure 79 below. Europe is in a vulnerable situation with regard to both energy and climate, together with the Asian-Pacific region. North America is less vulnerable to climate, but needs to improve its energy security position. It is likely that the European Union will continue to focus on renewable energy production to solve the climate and energy challenges. The Asian-Pacific region will remain focused on the short-term issues such as energy security and utilise its coal resources to provide that security. Even if climate change is quite a high risk for the region in the long-term, the short-term economic output is more important for these nations due to the relatively low per capita purchasing power.

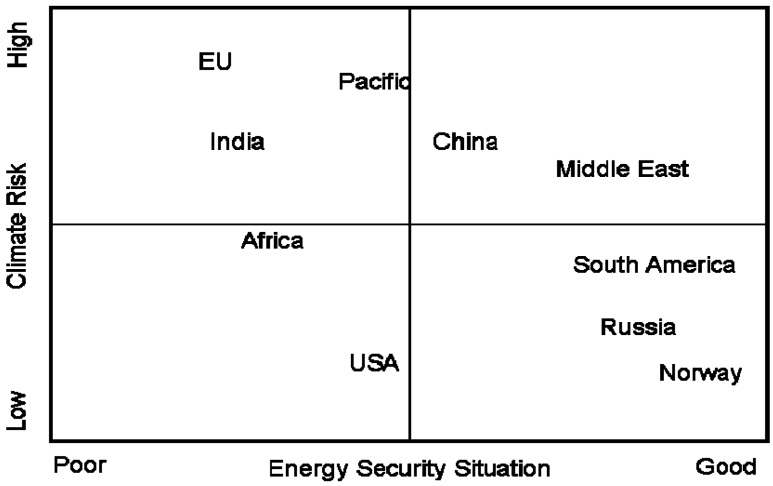


Figure 79: Energy Security and Climate risk

The drive for energy security seems far more important for most developed countries than the climate threat. Currently it seems unlikely that the world will agree on global climate-change policies due to the conflicting interests of different nations caused by differences in climate risk and energy security situations. The world population are facing significant challenges that might deserve higher attention than climate change such as providing food, fresh water and materials while avoiding severe conflicts over these resources (Watson and A.H.Zakri 2005). When economy and welfare are under pressure, humans tend to become short sighted, prioritising short-term income rather than long-term income. The reality of Maslow's (1952) hierarchy of needs becomes clear and visible in situations with increased stress, for persons, businesses and governments.

The value of renewable energy might increase substantially in the future when society realises the environmental impact of the use of fossil energy sources and establishes instruments to mitigate climate change due to increasing political pressure and change in customers' valuation of their environment. Understanding the impact of environmental damages due to CO_2 emissions on economic development is important to achieve change. Climate change will create pressure on society to develop instruments to reduce the risk of severe economic consequences. It is necessary to develop new ways of measuring sustainable economic development and new practices with respect to discounting of the environmental costs for future generations to be able to establish a price on CO_2 emissions. Achieving change is not an issue of economic optimisation, but of visions to secure the future.

A sustainable world would require a shift in economic thinking. Sustainable economic development will require:

- A shift in economic theory from growth to development.
- Coupling of economic models to the availability of limited natural resources.
- Measurement based on aggregated production capital, human capital and natural capital rather than Gross Domestic Product as today where the nation's capacity to sustain production on a long time scale is in focus.

Gross domestic product (GDP) is not a good measure of economic development but it is a good measure of economic costs (Dasgupta and Mäler 2001). Increasing environmental cost could in principle give an increasing GDP while it reduces the productive capacity of the country. A measure of sustainable development should be developed, focusing on the capacity of a nation, region or the world to sustain or maintain productive capacity per capita on a timescale of several decades.

5.7 A sustainable energy system

The world is facing at least two fundamental challenges; the environmental challenge caused by pollution from the use of fossil fuels for energy production, and the increasing scarcity of fossil energy sources. These two challenges, the **climate problem** and the **energy problem**, have the potential of causing major disruptions in economic growth for several regions of the world. Both challenges are caused by development in the past, pushing the limits of the environment beyond sustainability. If the world population is to aim for a sustainable society, the challenges the world population face will create opportunities within sustainable energy production in the 21st century (Schwartz 1998, p 14; Meadows, Randers et al. 2005, p 263).

A sustainable energy system should be capable of maintaining or increasing energy output indefinitely within the capacity of the ecosystem to absorb the emissions caused by energy consumption. To maintain energy output indefinitely, fossil-fuel production capital needs to be replaced by renewable energy production capital while the efficiency in the energy value chain improves in order to deliver an increasing energy output per unit of energy input. Due to energy security issues, carbon capture and storage may be part of the solution in countries with large coal resources such as the USA and China in the first half of this century.

There is a need to resolve the challenge of climate change within the next 15 to 20 years. If no commercially competitive renewable energy solution exists when the energy challenge emerges, caused by a peak in conventional oil production, coal will probably emerge as the solution to the most dominant problem at that time – the energy challenge. The climate change issue will probably be overshadowed by the energy challenge. Energy prices will increase, and policies that contribute to increased energy prices, such as CO_2 tax, will be politically difficult to establish and maintain.

Norway and Europe should focus on energy efficiency to use existing resources as efficiently as possible, and develop renewable energy sources that out-compete fossil-fuel sources. Using a large share of the limited fossil energy resources to remove CO_2 seems to be the wrong approach, although it will contribute to the solution of the climate problem. CCS will increase energy prices significantly as it will increase the demand for primary energy and add costs to electricity production.

5.8 Norwegian value creation in sustainable energy production

To allow for continued use of fossil fuels in a CO_2-restricted world, it will be necessary to develop CCS. As a majority owner in the national oil company, StatoilHydro ASA, it may be in the interest of the Norwegian government to support development of CCS to enhance the strategic value of StatoilHydro ASA. This thesis finds it unlikely that CCS can become an attractive business opportunity that will generate positive values in Norway. The main reasons are the limited future growth in the domestic market for fossil-fuelled power generation and CCS and the tax based financing. Norway may, however, offer storage capacity for European power companies on the Norwegian continental shelf.

Offshore wind power is a major opportunity for Norway, with and without climate policies in Europe. This thesis shows that an active policy in Norway to develop offshore wind energy can change the path of the energy system in Europe towards a renewable path. This will benefit both Norway and Europe in terms of value creation, energy security and climate mitigation. Sensitivities indicate that Europe will develop offshore wind power and achieve competitive advantages based on the energy security challenge, locking Norwegian offshore wind out of the market unless Norwegian industry has realised the opportunity before European industries. The opportunity for Norway is limited in time. Norway has to establish a renewable industry before Europe initiates strong incentives to develop such technologies, and before the energy challenge caused by peak petroleum overshadows the climate challenge. Peak petroleum will lead to increasing energy prices where policies that contribute to further increases in energy prices such as carbon tax may become impossible to defend.

Offshore wind power will generate increasing revenues for Norway as the technology moves down the learning curve, and the electricity prices increase as a consequence of decreasing fossil fuel supplies. Offshore wind development, based on the costs of the "Hywind" project of StatoilHydro ASA, with a 20 % learning rate and 6 % discount rate will generate positive values at current prices of 56 €/MWh. There are currently high risks for a commercial company in undertaking such a project where future energy prices are uncertain and current costs are clearly non-commercial. Initiating such a project would require substantial government support. However it would move Norwegian industry into a competitive position where the industrial development can create large values for the Norwegian society. Norway can provide a substantial fraction of the European electricity need by developing the offshore wind resource into a competitive energy provider, delivering 300–1000 TWh per year to the European market, and thus maintaining the cash flow from the Norwegian continental shelf. By developing the offshore wind industry, Norway can change the path of the European energy system, contribute to sustainability and increase accumulated gross domestic product in Norway by up to 25 % within this century.

5.9 Creating Norwegian competitive advantages

The Norwegian position with respect to developing offshore wind power is strong. Norway can become a stable and almost domestic provider of energy to Europe due to its financial strength, high competence in offshore development, marine technology and hydropower generation, and capacity to use hydropower to balance electricity supplies against demand.

Norway should, according to the Rio Declaration on Environment and Development, apply the precautionary principle to internalise environmental costs and apply economic instruments where the polluter bears the cost of pollution (UN 1992). Internalisation of environmental costs has not been widely implemented so far. Therefore, this thesis recommend Norway to increase the carbon tax to \$ 90/ton, to account for future environmental costs, and reinvest these tax revenues in new renewable energy production. A general renewable energy subsidy will be less efficient than a more focused subsidy towards offshore wind in terms of reductions in CO_2 emissions as shown in chapter 4.5.

Developing an offshore wind industry will require closer collaboration between governments and industry (Stern 2007, p 393). This development can be stimulated by a portfolio standard for CO_2 emissions or a carbon tax where the tax revenues are reinvested in new renewable energy production (Gerlagh and Zwaan 2006). Sensitivities using several different carbon tax and carbon market options in the CE2-model indicate that the most efficient approach in terms of reducing carbon dioxide emissions is a carbon tax set at around \$ 90–100/ton where the carbon tax revenues are reinvested in new renewable energy such as offshore wind. Such a policy would lead to extensive investments from commercial players in renewable energy. This will initiate a technological learning process which could lead to competitive advantages in energy production and CO_2 reductions for the benefit of Norway and Europe. The current carbon tax in Norway is \$ 30–\$ 55 per ton depending on use (Randers, Arnstad et al. 2006), generating revenues of approximately \$ 1.5 billion per year (SSB 2008). The Norwegian carbon tax should be raised gradually to twice the current level. All revenue from carbon tax should primarily be used as investment capital in new renewable energy production.

Due to the limited fossil fuel resources and the energy cost of CCS, the resources currently directed towards CCS may be better utilised by focussing on energy efficiency and renewable energy production (Nel and Cooper 2008). Norway should try to move out of the current "CCS blinding" where the R&D efforts in CCS drain the resources available for renewable research. This could move Norwegian industry into a leading position in this new industry, where strong advantages can be established. Norway seems to be in the innovator's dilemma (Christensen 1997, p xxii) where it has the choice between continued petroleum-based research or research on offshore renewable energy.

Porter (1990) found that nations succeed because their home environment is the most forward looking, dynamic, with a challenging domestic market. Creating future competitive advantages will require industry foresight, ability to shape the future industry structure to a Norwegian advantage, and development of a strong market position (Hamel and Prahalad 1994, p 50). It seems as if political leaders react to the challenges of the society in the same way as Machiavelli recommended:

> When a problem arises either from within a republic or outside it, one brought about either by internal or external reasons, one that has become so great that it begins to make everyone afraid, the safest policy is to delay dealing with it rather than trying to do away with it, because those who try to do away with it almost always increase its strength and accelerate the harm which they feared might come from it (Machiavelli 1979, p 240-241; quoted in Sterman 2000, p 8).

Developing a sustainable energy business requires vision to prioritise the development of competence and allocation of resources rather than pure economic optimisation based on current knowledge. A concern is the current neoclassical thinking in the Ministry of Finance, which is based on a weak sustainability position. It seems as if the main concern for the Ministry of Finance is short-term government spending and not long-term economic growth. The prevailing economic thinking seems to be that a wealthy society is better prepared to meet the challenges of the future, rather than investing to avoid the risks in the future.

In several nations, experience with subsidies through R&D programmes and feed-in tariffs has proved to be successful instrument to achieve a transition towards renewable energy. The creation of knowledge related to renewable energy, and offshore wind energy in particular, is vital to achieve competitive advantages. This can be achieved through public support to research and development within renewable energy. The Norwegian government established a feed-in tariff of 0.08 NOK/KWh for fifteen years of production in November 2006 (Stortingsmelding 2006). It remains to be seen how this will work out, but so far it seems insufficient to support onshore and offshore wind energy projects.

There are very few businesses in Norway that are capable of and willing to put in the necessary resources to lift offshore wind into a commercial business, except some of the oil and gas companies. These companies have more attractive investment options which will provide higher short-term revenues than offshore wind energy. Since change is difficult in existing successful companies, such as oil and gas companies, developing these disruptive innovations cannot be achieved within these organisations. An organisation formed to develop offshore wind in Norway has to be large enough in terms of competence and financial strength to become the major driving force of this development. Development of a totally new business within an existing business is, as described in chapter 2.6, unlikely to succeed.

To create scale economics and competitive advantages for offshore wind power, and to avoid fragmented efforts, it seems reasonable to establish a state-owned company, “StatWind”, based on the experiences of the Norwegian oil and gas industry. CO_2 taxes could be reinvested into the company as equity capital. History has shown that the

Norwegian industry policy, with its strong government ownership in important national industries, has proved to be efficient as a tool for industry development in Norway. Examples of successful companies are Telenor, Hydro and Statoil. These former state-owned companies are now partly privatised. The offshore wind energy is a significant national resource with substantial risks for commercial companies and large capital requirements. A national offshore wind company should develop and operate infrastructure and facilities on the Norwegian Continental Shelf, and would contribute to create the benefit of economies of scale with associated substantial cost reductions. The company would have to invest between $ 2 billion and $ 4 billion per year. When this company becomes a fully commercial business, the values could be harvested through a privatisation of the company. The operating company should utilise domestic and international industrial competence and capabilities to develop as a competitive energy provider. This would result in large development contracts to Norwegian and international industries – such as the Danish wind-turbine industry and Norwegian shipyards, and create the drive and rivalry within Norwegian industry to develop competitive advantages.

5.10 Critique

This thesis has tried to identify strategic opportunities for Norway in sustainable energy production. The approach, by use of a system dynamic simulation model, has created insights into the problem that otherwise would have been harder to achieve. The CE2-model is complex, maybe too complex.

> The more complex and large a business, the more complex and large the scope of the scenarios. Thus, scenarios have to be simple, dramatic, and bold – to cut through the complexity and aim directly at the heart of an individual decision (Schwartz 1998, p 193).

A simpler model would have been preferable, but simplifications lead to reduced dynamic insight as important feedback mechanisms are excluded. The approach in this study has been to incorporate many details initially, and then remove those that seem to be less important in the time perspective and problem that is investigated. The CE2-model is useful for the purpose of this work. The CE2-model is not capable of reproducing the historical development of energy prices because of political influence on the energy investments and supplies from major oil and gas producing nations, which lead to a non-equilibrium behaviour. The CE2-model is, however, capable of modelling the underlying cost development of energy production. The main mechanisms that influence the future energy system will probably be different from the past; leading to the conclusion that historic behaviour may be less important.

The CE2-model includes a response by energy prices to demand and energy efficiency improvements which reflects observations in the US market (Unander 2004). There are significant uncertainties related to how this process works. Energy efficiency improvements as a response to increasing energy prices may reduce the future energy demand significantly. Energy efficiency improvements are likely to be partly offset by the rebound effect, which can reduce the benefit of energy efficiency improvements by up to 60 % (Frondel, Peters et al. 2008).

Finally, as Solow (2000, p xxvi) warned, this thesis may "try to do more than can be done". Further research is recommended on issues such as:

- Non-energy related CO_2 emissions
- A thorough assessment of global fossil resources
- Structure and organisation of a renewable energy industry
- CO_2 market or tax mechanisms as tools to reduce emissions
- Incorporate natural resources into economic theory
- Develop indexes for sustainable economic development to replace GDP

6 Conclusion

The threat of “peak petroleum” is significant and could lead to economic recession for several decades unless the world prepares for a smooth transition to renewable energy. Norwegian oil production has passed the peak. Norway needs to develop industries that can replace the value creation from the oil and gas production within a few decades to maintain the current welfare level. Offshore wind is one attractive option capable of generating such values.

Increasing scarcity of natural resources such as oil, gas and water might lead to increasing geopolitical tension and armed conflicts leading to difficulties in maintaining sufficient investments in energy production and infrastructure in the energy-rich regions. This will lead to increased energy prices and increasing value of renewable energy production.

This study finds that the fossil-fuel resources available are unlikely to cause a catastrophic climate development because the temperature increase caused by energy-related CO_2 emissions probably will be below 3^{o}C. Reproducing the CO_2 emissions scenarios by IPCC will require fossil-fuel resources three times higher than estimated by IEA, which seems unlikely. Coal and unconventional oil resources, however, may change this conclusion. Extensive use of these resources will require CCS to avoid severe climate change.

Climate change may lead to severe changes in the long run, and the precautionary principle should apply to global climate policies. This study finds that a policy based on a carbon tax which is reinvested in renewable energy production is the most efficient in terms of accelerating investments in renewable energy production and CCS to reduce CO_2 emissions significantly. This thesis finds that a carbon tax of \$ 90/ton will not have any negative effects for the world economy.

The potential value creation in offshore wind power on the Norwegian Continental Shelf is significant, and can increase accumulated GDP by more than 10 % by the year 2100 given that Norway acts early to create competitive advantages towards European industries. Because limited climate changes will enhance the value of Norwegian offshore wind resources due to increased European energy demand, it is in the interest of Norway to work towards a strong international climate agreement.

CCS will at best be a zero-sum game for Norway, although it may be an important technology for the world to allow for the continued use of fossil fuels without large impacts on climate. The current situation, with limited fossil fuel resources, should call for increased focus on energy saving and energy efficiency rather than wasting limited energy resources on carbon capture and storage.

Norway can develop the offshore wind power industry into a business capable of replacing the declining value creation from the Norwegian oil and gas industry. This will require stable policies and instruments such as:

- Include the environmental costs of CO_2 emissions in the cost of energy and products through a carbon tax of $90/ton (Internalise externalities).
- Recycle carbon tax back to new renewable energy investments.
- Establish public procurement programmes where governments require a high degree of renewable energy in public purchases.
- Increase public R&D on renewable energy production.

These instruments will probably be sufficient to achieve a transition towards a more sustainable energy system in Norway. To achieve a more rapid, large scale transition to deliver electricity to Europe, other more powerful instruments are necessary. Establishment of a state-owned company in offshore renewable energy could be such a strong instrument to achieve fast and large-scale transition toward renewable energy production. The real confirmation of a strong interest in this industry is that governments and companies allocate capital and their best personnel resources towards renewable energy. To develop a sustainable energy system, governments have to decide to leave a healthy environment for future generations, and put words into action.

Mostly we know what to do but we lack the will to do it.
Sir Crispin Tickell (quoted in Houghton 2004, p 210)

References

Aghion, P. and P. Howitt (1998). Endogenous Growth Theory, The MIT press.

Al-Fattah, S. M. and R. A. Startzman (2000). Forecasting World Natural Gas Supply 2000 SPE/CERl Gas Technology Symposium Calgary, Canada, , SPE.

Aleklett, K. (2006). Exploring the evidence of peak oil production. Energy Foresight Symposium, Bergen.

Alphen, K. v., J. v. Ruijven, et al. (2009). "The performance of the Norwegian carbon dioxide, capture and storage innovation system." Energy Policy **37**: 43-55.

Ansolabehere, S., J. Beer, et al. (2007). The Future of Coal. Massachusetts, MIT.

Archer, D. (2007). Global Warming. Malden, MA, USA, Blackwell Publishing.

Argyris, C. (1990). Overcoming Organizational Defences, Facilitating Organizational Learning. Cambridge, University Press.

Atkinson, G. (2000). "Re-thinking Economic Progress " WORLD ECONOMICS **1**(1): 153-166.

Auken, S. (2002). "Answers in the wind: How Denmark became a world pioneer in wind power." The Fletcher forum of world affairs **26**(1).

Ayres, R. (1996). "TECHNOLOGY, PROGRESS AND ECONOMIC GROWTH " European Management Journal **14**(6).

Ayres, R. U. (2001). "The minimum complexity of endogenous growth models: the role of physical resource flows " ENERGY **26**: 817-838.

Ayres, R. U. (2006). "On the practical limits to substitution " ECOLOGICAL ECONOMICS **61**: 115-128.

Ayres, R. U. and B. Warr (2005). "Accounting for growth: the role of physical work " Structural Change and Economic Dynamics **16**: 181-209.

Barro, S.-i.-M. (2004). Economic Growth. Cambridge, MA, The MIT Press.

Baumol, W. J. (2003). "Innovation and growth: two common misapprehensions." Journal of Policy Modelling.

Beckerman, W. (2001). "Economists and Sustainable Development " WORLD ECONOMICS **2**(4): 1-17.

Belhaj, H. A. and T. Lay (2008). Future Projection of Energy Prices: A Predictive Model 2008 SPE Western Regional and Pacific Section AAPG Joint Meeting. Bakersfield, California, U.S.A., SPE.

BP (2007). BP Statistical review of world energy.

Brundtland, G. H. (1987). Our Common Future. Oxford, Oxford University Press.

Bush, G. W. (2006). State of the Union Address, White House.

Bush, G. W. (2008). "FY2008." from www.whitehouse.gov.

Bush, G. W. (2008). State of the union address. W. House.

CERA (2006). Dawn of the ages. London, Cambridge Energy Research Associates.

Christensen, C. (2004). Seeing what's next, Harvard Business School Publishing Corporation.

Christensen, C. M. (1997). The innovator's dilemma, Harvard Business School Press.

Christensen, C. M., S. P. Kaufman, et al. (2008). Innovation Killers. Harvard Business Review**:** 98-105.

Cohen, B. and M. I. Winn (2005). "Market imperfections, opportunity and sustainable entrepreneursliip " Journal of Business Venturing.

Correlje, A. and C. v. d. Linde (2006). "Energy supply security and geopolitics: A European perspective " Energy Policy **34**: 532-543.

Cox, P. M., R. A. Betts, et al. (2000). Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model Nature. **408:** 184-187.

Cramer, J. (2006). Corporate Social Responsibility and Globalisation. Sheffield, UK, Greenleaf Publishing Ltd.

Daly, H. E. (1996). Beyond Growth. Boston, MA, Beacon Press.

Daly, H. E. (2005). "Economics in a full world." Scientific American: 78-85.

Daly, H. E. and J. Farley (2004). Ecological Economics. Washington DC, Island Press.

Dasgupta, P. and K.-G. Mäler (2001). "Wealth as a Criterion for Sustainable Development " WORLD ECONOMICS **2**(3): 19-44.

Davidsen, P. I., J. D. Sterman, et al. (1990). "A petroleum life cyckle model for the United States with endogenous technology, exploration, recovery and demand." System Dynamics Review **6**(1): 66-93.

Davidsson, P. (2004). Researching Entrepreneurship, Springer.

Demirbas, A. (2008). "Biofuels sources, biofuel policy, biofuel economy and global biofuel projections " Energy Conversion and Management

Deutch, J. (2005). What should the government do to encourage technical change in the energy sector?, MIT Joint Program on the Science and Policy of Global Change.

Deutch, J., E. J. Moniz, et al. (2003). The Future of Nuclear Power, MIT.

EC (2002). Report on Research and Development, European Commission.

Economides, M. and R. Oligney (2000). The Colour of Oil. Katy, TX, Round Oak Publishing Company, Inc.

Ediger, V. S., E. Hosgör, et al. (2007). "Fossil fuel sustainability index: An application of resource management." Energy Policy **35**: 2969-2977.

ENOVA (2007). Potensialstudie av havenergi i Norge. Trondheim, ENOVA SF.

ENOVA (2007). Potensialstudie for havenergi i Norge, ENOVA SF.

Ergas, H. (1987). The importance of technology policy. Economic policy and technological performance. P. Dasgupta and P. Stoneman. Cambridge, Cambridge University Press.

Esser, R. (2005). The oil industry growth challenge: expanding production capacity. Testimony to US house of representatives. Washington DC.

ETSAP. (2008). "Energy Technology Systems Analysis Programe." from www.etsap.org.

Farrell, A. and D. Kammen (2007b). Transport requirement per capita.

Farrell, A. E. and A. R. Brandt (2006). "Risks of the oil transition " Environmental Research Letters.

Fiddaman, T. (2007). "Dynamics of climate policy." System Dynamics Review **23**(1): 21-34.

Fiddaman, T. S. (1997). Feedback Complexity in Integrated Climate-Economy Models. Department of Operations Management and System Dynamics. Massachusets, Massachusets Institute of Technology. **PhD**.

Fiddaman, T. S. (2002). "Exploring policy options with a behavioral climate-economy model." System Dynamics Review **18**(2): 243-267.

Field, C. B., J. E. Campbell, et al. (2007). "Biomass energy: the scale of the potential resource " Trends in Ecology and Evolution (In press).

Fisher, C. and R. Newell (2003). Environmental and Technology Policies for climate change and renewable energy, Resources for the future.

Fortson, D. (2008). Stern warns that climate change is far worse than 2006 estimate THE INDEPENDENT London.

Foxon, T. J., R. Gross, et al. (2005). "UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures." Energy Policy **33**(16): 2123-2137.

Frondel, M., J. Peters, et al. (2008). "Identifying the rebound: Evidence from a German Household panel." The Energy Journal **29**(4): 145-163.

Gately, D. (2007). "What oil export levels should we expect from OPEC?" The Energy Journal **28**(2): 151-173.

Georgescu-Roegen, N. (1971). The Entropy Law and the Economic Process. Cambridge, MA, Harvard University Press.

Gerlagh, R. and B. v. d. Zwaan (2006). "Options and Instruments for a deep cut in CO2 emissions: Carbon Dioxide Capture or Renewables, Tax or Subsidies?" The Energy Journal **27**(3): 25-48.

Gether, H. (2007). STORSKALA VINDKRAFT UTENFOR NORD-NORGE, Bodø.

Gether, K. (2004). Transition to large scale use of hydrogen and sustainable energy services. Department of Energy and Process Engineering. Trondheim, Norwegian University of Science and Technology. **PhD**.

Gotaas, S. (2008). Energi21 - en samlende FoU strategi for energisektoren.

Greene, D. L., J. L. Hopson, et al. (2006). "Have we run out of oil yet? Oil peaking analysis from an optimist's perspective " Energy Policy **34**: 515-531.

Grubb, M., J. Köhler, et al. (2002). "Induced Technical Change in Energy and Environmental Modeling; Analytic Approaches and Policy Implications." Annual Reviews on Energy and Environment: 271-308.

Hamel, G. and C. K. Prahalad (1994). Competing for the future, Harvard Business School Press.

Hirsch, R. L., R. Bezdek, et al. (2005). Peaking of world oil production: impacts, mitigation and risk management, SAIC.

Houghton, J. (2004). Global Warming. Cambridge, UK, Cambridge University Press.

IEA (2004). World Energy Outlook, International Energy Agency.

IEA (2006a). Energy Technology Perspectives - Scenarios & Strategies to 2050, International Energy Agency.

IEA (2006b). World Energy Outlook 2006, OECD/IEA.

IEA (2007). World Energy Outlook 2007, OECD/IEA.

IEA (2008a). Energy Technology Perspectives - Scenarios & Strategies to 2050, International Energy Agency.

IEA (2008b). World Energy Outlook 2008. I. E. Agency.

Iledare, O. and A. Pulsipher (1999). The State of the Global E&P Industry: Is the World Running Out of Oil? . SPE Annual Technical Conference and Exhibition, Houston, Texas, Society of Petroleum Engineers Inc. .

IPCC (2007a). Climate Change 2007 - The Physical Science Basis. Cambridge, Cambridge University Press for the Intergovernmental Panel Of Climate Change.

IPCC (2007b). Climate Change 2007 - Impacts, Adaptation and Vulnerability. Cambridge, Cambridge University Press for the Intergovernmental Panel Of Climate Change.

IPCC (2007c). Climate Change 2007 - Mitigation of climate change, Cambridge University Press.

Isoard, S. and A. Soria (2001). "Technical change dynamics: evidence from the emerging renewable energy technologies " Energy Economics **23**: 619-636.

ITER. (2005). "The ITER project." 2005, from http://www.iter.org/a/index_nav_1.htm.

Jaccard, M. (2005). Sustainable Fossil Fuels. Cambridge, Cambridge University Press.

Jacobsson, S. and V. Lauber (2006). "The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology." Energy Policy **34**(3): 256-276.

Jones, C. I. (2002). Economic Growth. London, W.W.Norton & Company Ltd.

Jungbluth, N., M. Tuchschmid, et al. (2008). "Life Cycle Assessment of Photovoltaics: Update of ecoinvent data."

Kalicki, J. H. and D. L. Goldwyn (2005). Energy & Security. Washington, D.C., Woodrow Wilson Center Press.

Kara, M., S. Kullander, et al. (2008). Thorium as an Energy Source - Opportunities for Norway Oslo, The research council of Norway.

Kaufmann, R. K., S. Dees, et al. (2008). "Oil Prices: The Role of Refinery Utilization, Futures Markets and Non-Linearities " Energy Economics

Kay, A. (1994). The best way to predict the future is to invent it. G. H. May. London.

Keeney, R. L. (1992). Value-Focused Thinking. Cambridge, Harvard University Press.

Landström, H. (2005). Entreprenörskapets rötter. Lund, Studentlitteratur.

Lazonick, W. (2003). "The theory of the market economy and the social foundations of innovative enterprise." Economic and Industrial Democracy.

Lucas, R. E. (1988). "On the mechanisms of economic development." Journal of Monetary Economics **22**: 3-42.

Lund, P. D. (2007). "Effectiveness of policy measures in transforming the energy system." Energy Policy **35**(1): 627-639.

Löschel, A. (2002). "Technological change in economic models of environmental policy: a survey " Ecological Economics **43**: 105-126.

Løvås, J. (2008). Dagens Næringsliv. Oslo**:** 10, 12 Aug 2008.

Machiavelli (1979). Discources. The Portable Machiavelli. Bondanella. New York, Viking Press.

Maréchal, K. (2007). "The economics of climate change and the change of climate in economics." Energy Policy **35**: 5181-5194.

Maslow, A. (1952). Management and Motivation. Englewoods Cliffs, NJ, Prentice Hall.

May, G. H. (1996). The Future is Ours, Praeger Publishers.

Meadows, D., J. Randers, et al. (2005). Limits to Growth - the 30 year update, Earthscan.

Meadows, D., J. Randers, et al. (1972). Limits to Growth, Universe Books.

Monbiot, G. (2007). HEAT - How to stop the planet from burning. Cambridge, MA, South End Press.

Montgomery, C. A. (2008). Putting leadership back into strategy. Harvard Business Review**:** 54-60.

Mouawad, J. (2008). Oil Price Rise Fails to Open Tap The New York Times. New York.

Moxnes, E. (2000). "Not only the tragedy of the commons: misperceptions of feedback and policies for sustainable development." System Dynamics Review **16**(4): 325-348.

Mun, J. (2006). Real Options Analysis. New Jersey, John Wiley & Sons.

Mørch, H. H. (2007). Økonomiske rammebetingelser og anleggsomkostninger. Oscarsborg Festning.

Nel, W. P. and C. J. Cooper (2008). "Implication of fossil fuel constraints on economic growth and global warming." Energy Policy.

Neuhoff, K. (2008). "Learning by doing with constrained growth rates: An application to energy technology policy." The Energy Journal(Spesial Issue): 165-182.

Newell, R. G., A. B. Jaffe, et al. (2006). "The effects of economic and policy incentives on carbon mitigation technologies." Energy Economics **28**: 563-578.

Nordhaus, W. (2007). Critical Assumptions in the Stern Review on Climate Change Science. **317:** 201-202.

Nordhaus, W. D. and J. Boyer (2000). Warming the world – Economic models of Global Warming, The MIT Press.

Nordpool. (2008). "Average El Spot prices." from http://www.nordpool.com/system/flags/elspot/area/all/.

NPD (2005). Total Petroleum Production 1970-2030. Stavanger, NPD - Norwegian Petroleum Directorate**:** Total Petroleum Production on the Norwegian Continental Shelf 1970-2030.

NPD. (2007). "Sokkelåret 2007." from http://www.npd.no/Norsk/Aktuelt/Pressemeldinger/2008/14.1.2008+Sokkelaaret_pressemelding.htm.

NRK (2008). Gazproms verden, NRK, 12 december 2008.

Nuttall, W. J. and D. L. Manz (2008). "A new energy security paradigm for the twenty-first century " Technological Forecasting and Social Change.

Owen, A. D. (2006). "Renewable energy: Externality costs as market barriers." Energy Policy **34**(5): 632-642.

Paine, C. (2007). The Electrification of vehicles. UC Berkeley Stanford CleanTech Conference Series, UC Berkeley.

Pearson, P. N. and M. R. Palmer (2000). Atmospheric carbon dioxide concentrations over the past 60 million years Nature. **406:** 695-699.

Perez, C. (2003). Technological revolutions and financial capital. Cheltenham, UK, Edward Elgar.

Persson, G. (2006). På väg mot et oljefritt Sverige, Regeringskansliet.

Pielke, R., T. Wigley, et al. (2008). Dangerous assumptions Nature**:** 531-532.

Pittock, B. (2005). Climate Change - turning up the heat, Earthscan.

Polak, F. (1973). The Image of the future. Oxford, Elsevier.

Popp, D. (2006). "Innovation in climate policy models: Implementing lessons from the economics of R&D " Energy Economics **28**: 596-609.

Porter, M. (1980). Competitive Strategy, The Free Press.

Porter, M. (1990). "The Competitive Advantage of Nations." Harvard Business Review(March/April 1990).

Porter, M. (1994). From Competitive Advantage to Corporate Stategy. Strategy. B. D. Wit and R. Meyer, West Publishing Company**:** 274-287.

Porter, M. E. (2008). The five competitive forces that shape strategy. Harvard Business Review**:** 79-93.

Randers, J. (2000). "From limits to growth to sustainable development." System Dynamics Review **16**(3): 213-224.

Randers, J., E. Arnstad, et al. (2006). Et Klimavennlig Norge.

Reynolds, D. B. (1999). "Entropy and diminishing elasticity of substitution " Resources Policy
25: 51-58.

Rodrik, D. (1999). "How far will international economic integration go?"

Romer, P. M. (1986). "Increasing returns and Lng-run growth." Journal of Political Economy **94**: 1002-1037.

Ruth, S. (2005). A global sense of energy insecurity, CERA.

Sabine, C. L., R. A. Feely, et al. (2004). "The Ocean Sink for Antropogenic CO2." Science **305**.

Sagar, A. D. and B. v. d. Zwaan (2006). "Technological innovation in the energy sector: R&D deployment and learning-by-doing." Energy Policy **34**(17): 2601-2608.

Sand, G., M. Schiefloe, et al. (2005). Norge 2020, Fagbokforlaget.

Schleich, J. and E. Gruber (2008). "Beyond case studies: Barriers to energy efficiency in commerce and the services sector " Energy Economics **30**: 449-464.

Schrattenholzer, L., A. Miketa, et al. (2004). Achieving a sustainable global energy system, Edward Elgar Publishing, Inc.

Schumpeter, J. (1934). The theory of economic development, Harvard University Press.

Schwartz, P. (1998). The Art of the long view, John Wiley & Sons Ltd.

Shane, S. (2003). A general theory of Entrepreneurship. Cheltenham, UK, Edward Elgar.

Shell. (2005). "The Shell Global Scenarios to 2025." from www.shell.com.

Siegenthaler, U., S. Thomas F, et al. (2005). Stable Carbon Cycle-Climate Relationship During the Late Pleistocene Science. **310:** 1313-1317.

Simmons, M. R. (2005). Twilight in the Desert. Hoboken, NJ, John wiley Sons, Inc.

Simmons, M. R. (2008). "Quo Vadis Energy? (Will Dawn Follow Darkness As Twilight Of Energy Fades?)." Retrieved May 30, 2008, from http://www.simmonsco-intl.com/research.aspx?Type=msspeeches.

Smit, H. T. J. and L. Trigeorgis (2004). Strategic Investment - Real Options and Games. oxford, Princeton University Press.

Solow, R. M. (2000). Growth Theory - An Exposition. Oxford, Oxford university Press.

SSB. (2008). "Miljøskatter i Norge." from http://www.ssb.no/magasinet/miljo/tab-2005-09-05-01.html.

StatoilHydro. (2008). "Verdens første fullskala flytende vindmølle." Retrieved 10 June 2008, from http://www.statoilhydro.com/no/TechnologyInnovation/NewEnergyAndRenewables/Wind/VindTilHavs/Pages/Hywind.aspx.

Sterman, J. D. (1981). The energy transition and the economy: A system dynamics approach, MIT Sloan School of Management.

Sterman, J. D. (2000). Business Dynamics - Systems Thinking and Modeling for a Complex World, The McGraw-Hill Companies Inc.

Stern, N. (2007). The economics of climate change: The Stern Review, Cambridge University Press.

Stiglitz, J. E. (1987). Learning to learn, localized learning and technology progress. Economic Policy and technological Performance. P. Dasgupta and P. Stoneman. Cambridge, Cambridge University Press.

Stortingsmelding (2005). Stortingsmelding nr 21: Regjeringens Miljøvernpolitikk og rikets miljøtilstand. N. M. o. Environment.

Stortingsmelding (2006). Stortingsmelding nr 11: Om støtteordningen for elektrisitetsproduksjon fra fornybare energikilder. N. M. o. P. a. Energy.

Stortingsmelding (2009). Stortingsmelding nr 9: Perspektivmeldingen 2009. N. M. o. Finance.

Söderholm, P., K. Ek, et al. (2007). "Wind Power Development in Sweden: Global policies and local obstacles." Renewable and Sustainable Energy Reviews **11**(3): 365-400.

Tao, Z. and M. Li (2007). "System dynamics model of Hubbert Peak for China's oil." Energy Policy **35**: 2281-2286.

Tester, J. W., B. J. Anderson, et al. (2006). The Future of Geothermal Energy. Massachusetts, MIT.

Thirlwall, A. P. (2006). Growth & Development. New York, Palgrave MacMillan.

Tilton, J. E. (1996). "Exhaustible resources and sustainable deveJopment, two different paradigms." Resources Policy **22**: 91-97.

Tollefson, J. (2008). Not your fathers biofuels Nature. **451:** 880-883.

Toth, F. L. (1995). "Practice and progress in integrated assessments of climate change." Energy Policy **23**: 253-268.

Turton, H. (2006). "Sustainable global automobile transport in the 21st century: An integrated scenario analysis " Technological Forecasting and Social Change **73**: 607-629.

UN (1992). Rio declaration on environment and development. Rio de Janeiro, UN.

UN. (2006). "World Population Prospects: The 2006 revision." Retrieved 30 January 2009, from http://esa.un.org/unpp/.

Unander, F. (2004). "Thirty years of energy prices and savings." Energy Prices and Taxes.

Utterback, J. M. (1996). Mastering the Dynamics of Innovation. Boston, MA, Harvard Business School Press.

Victor, D. G., A. M. Jaffe, et al., Eds. (2006). Natural Gas and Geopolitics. Cambridge, UK, Cambridge University Press.

Vries, B. J. M. d., D. P. v. Vuuren, et al. (2007). "Renewable energy sources: Their global potential for the first-half of the 21st century at a global level: An integrated approach " Energy Policy **35**: 2590-2610.

Wald, M. L. (2008). Wind Energy Bumps Into Power Grid's Limits. The New York Times. New York.

Wang, Y. (2008). "Millennial- and orbital-scale changes in the East Asian monsoon over the past 224000 years." Nature **451**(7182): 1090-1093.

Watson, R. T. and A.H.Zakri, Eds. (2005). Millenium Ecosystem Assessment. Washington DC, World Resource Institute.

Webster, M., S. Paltsev, et al. (2008). "Autonomous efficiency improvement or income elasticity of energy demand: Does it matter?" Energy Economics **30**: 2785-2798.

WEC (2007). 2007 Survey of Energy Resources, World Energy Council.

WorldBank (2006). World Development Indicators 2006, World Bank.

Yergin, D. (2006). "Ensuring Energy Security." Foreign Affairs **85**(2): 69-82.

Zachos, J., M. Pagani, et al. (2001). Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present. Science. **292:** 686-693.

Zittel, W. and J. Schindler (2006). Uranium Resources and Nuclear Energy Ottobrunn Energy Watch Group

Zittel, W. and J. Schindler (2007). Coal: Resources and Future Production Ottobrunn, Energy Watch Group