“Subsidising carbon capture: effects on energy prices and market shares in the power market”

AUTHORS	Finn Roar Aune Gang Liu Knut Einar Rosendahl Eirik Lund Sagen
ARTICLE INFO	Finn Roar Aune, Gang Liu, Knut Einar Rosendahl and Eirik Lund Sagen (2010). Subsidising carbon capture: effects on energy prices and market shares in the power market. *Environmental Economics*, *1*(1)
RELEASED ON	Friday, 05 November 2010
JOURNAL	"Environmental Economics"
FOUNDER	LLC “Consulting Publishing Company “Business Perspectives”

Finn Roar Aune (Norway), Gang Liu (Norway), Knut Einar Rosendahl (Norway), Eirik Lund Sagen (Norway)

Subsidising carbon capture: effects on energy prices and market shares in the power market

Abstract

This paper examines how ambitious climate policies and subsidies to carbon capture may affect international energy prices and market shares in the power market. A detailed numerical model of the international energy markets is used in this study. We first conclude that an ambitious climate policy alone will have substantial effects in the power market, with considerable growth in renewable power production and eventually use of carbon capture. Gas power production will also benefit from such a policy. Subsidising carbon capture and storage (CCS) will significantly accelerate the use of this technology. Nevertheless, total production of coal and gas power (with or without CCS) is only marginally increased, as the subsidy mainly leads to installation of CCS equipment on existing plants, reducing the efficiency from these plants. Consequently, electricity prices are almost unchanged, and the substantial growth in renewable power production is hardly affected by the subsidies to CCS.

Keywords: energy markets, climate policy, carbon capture.
JEL Classification: H23, Q40, Q54.

Introduction

Recognizing that emissions of greenhouse gases (GHG) contribute significantly to climate change, there is growing support worldwide for setting ambitious targets to reduce such emissions[1]. It is clear that such targets will never be met without substantial reduction of CO_2 emissions from the power sector. The use of fossil fuels in power generation, primarily coal and gas, accounts for about 41 percent of all CO_2 emissions in the world (IEA, 2007a, p.195).

Given the large share of fossil fuels in current and projected power generation (EIA, 2008; IEA, 2007a), measures to address climate change will most likely embrace solutions for power generation from fossil fuels with radically reduced CO_2 emissions. In this sense, technologies for carbon capture and storage (CCS) may play a crucial role in a portfolio of existing and emerging technologies. CCS technologies remove CO_2 emissions from stationary sources such as power plants, production of synthetic transport fuels and other industry processes, for storage in geologic formations or the ocean. Mineral storage is another possibility. Carbon capture allows for continued utilization of conventional fossil fuels while significantly reducing carbon emissions.

Carbon capture is high on the energy policy agenda in most OECD countries. The EU Strategic Energy Technology Plan recognizes the demonstration of the use of CCS in power generation as one of the focus areas for European technology development (EU, 2007)[2]. The Obama administration is expected to introduce a major change in US energy and climate policies, including support for power plants with CCS[3]. Carbon capture is also high on the policy and/or research agenda in other OECD countries like Japan, Canada and Australia. Non-OECD countries are generally less focused on CCS, but not ignorant[4]. Clearly, the gradual introduction and diffusion of power generation with CCS technologies throughout the world will reshape the international energy markets.

A number of studies by means of either national or global energy-environment models (e.g., Edmonds et al., 2002; Johnson and Keith, 2004; McFarland et al., 2004; IEA, 2006, 2007a; *The Energy Journal*, Special Issue, 2006; Martinsen et al., 2007) and several reviews (e.g., IPCC, 2005; IEA, 2007b) have made assessments on CCS technologies as one of the potential options for mitigating climate change. The focuses of these studies and reviews are primarily on availability, timing and costs of CCS for mitigating climate change. In general, they find that CCS technologies are already technically feasible and could play an important role in reducing carbon emissions, but only if policies that impose a sufficiently high implicit or explicit price on such

[1] For instance, the EU has set ambitious goals for own emissions in 2020, with deeper cuts expected beyond 2020 (EU, 2008a). In the US, The American Clean Energy and Security Act including an economy-wide cap-and-trade system was passed by the US House of Representatives in June 2009 (http://energycommerce.house.gov/index.php? option=com_content&view=article&id=1633&catid=155&Itemid=55).

[2] To stimulate development of carbon capture, the European Commission proposes an enabling regulatory framework and the inclusion of CCS in the EU emission trading scheme (ETS). To make early demonstration feasible, major financial commitments are needed (EU, 2008b).

[3] In The American Clean Energy and Security Act (see footnote 1), carbon capture plays a significant role as a "clean energy", with specific programs for demonstration and early deployment.

[4] For instance, in China a pilot project capturing CO_2 from a coal power plant has been launched (http://www.sciencedaily.com/releases/2008/07/080731135924.htm).

emissions are in place. For large emission reductions and high carbon prices, access to CCS technologies substantially lowers the total mitigation costs. It has been suggested that a significant number of new plants with carbon capture could enter the power supply sector within the next few decades, whereas retrofits with CCS technologies included could enter in just a few years given a sufficiently high price on emissions (IPCC, 2005; Newell et al., 2006).

Instead of focusing on availability, timing and costs of CCS technologies, this paper looks into how carbon capture may influence the international energy markets, in a world with ambitious climate policies possibly combined with subsidies to CCS. In particular, we examine the effects on market shares of coal and gas power of subsidizing carbon capture, and the effects on gas, coal and electricity prices. This should be of significant interest for both policy makers, investors in the energy market, and for big energy consumers. For instance, the impacts of CCS subsidies on investments in renewable power depend highly on the effects on electricity prices, which again depend inter alia on the effects on fossil fuel prices.

We first present a brief analytical Section where we derive some interesting conclusions. Then we present simulation results based on a detailed numerical model. With much uncertainty about current and future costs of CCS technologies, we support our conclusions with several sensitivity analyses.

To our knowledge, few if any previous studies have looked into the potential effects on international energy prices of introducing CCS into the market, either through CO_2 taxes or direct subsidies to CCS, and the subsequent effects on market shares in the power market. In a somewhat related study, Golombek et al. (2009) investigate the long-run relationship between CO_2 tax levels and market shares of different CCS technologies in the European power market. Their study is different from ours both with respect to focus and choice of simulation model. For instance, whereas they use a long-run static equilibrium model with perfect foresight for the European energy market, we use a recursively-dynamic equilibrium model with adaptive price expectations for the global energy markets. Thus, the two studies may be viewed as complementary.

The future importance of CCS will crucially depend on how its costs develop through technological progress. Recent years have witnessed an increasing emphasis on analysing the potential of policy induced technological change for addressing the climate change problem[1]. Technological progress is a product of several distinct forces, typically classified into: (1) R&D – public and private sector knowledge investment, or so-called "learning by searching"; and (2) LbD – reducing the costs of existing technologies through "learning by doing" (Grubb et al., 2006).

Market-oriented measures such as carbon taxes and tradable emission permits will lead to innovation and improvements in low-carbon technologies such as CCS by stimulating R&D and LbD (see, e.g. Requate and Unold, 2003)[2]. However, due to the presence of spillovers of knowledge, both from R&D and LbD, the market will most likely undersupply new technologies even if the price of greenhouse gas emissions is set correctly, i.e. at the Pigouvian level (Hart, 2008). Moreover, along with the globalization of markets, technological change is mainly an international process today, which means that the development of CCS technologies in one country will be influenced by the development elsewhere. Therefore, direct support of technological innovations may be needed, possibly at the international level. Spillover effects may exist not only across countries or regions, but also across different types of power plants and technologies. For example, the development of CCS technologies in gas power plants may benefit from that in coal power plants, and *vice versa*.

Whereas spillovers from R&D may call for R&D subsidies or other research policies, spillovers from LbD may call for subsidies to adoption of CCS technologies. The optimal policy mix is obviously difficult to sort out, both from a national and a global point of view, and is not the topic of this paper. Instead we are interested in the energy market effects of extensive adoption subsidies, combined with high CO_2 prices, which seem to be high on the agenda in many countries.

There exist a variety of capture methods, which can be broadly classified as post-combustion, precombustion and oxy-combustion. In post-combustion a solvent is used to capture CO_2 from the flue gas of power plants. This method can be considered a current technology, but its demonstration at large-scale power plants is needed. Thus, LbD

[1] See, e.g. Greaker and Rosendahl (2008), Hart (2008), Kverndokk and Rosendahl (2007), Gerlagh and van der Zwaan (2006) and *The Energy Journal*, Special Issue (2006).

[2] For instance, as a direct response to a high carbon tax imposed by the Norwegian government in 1991, the company Statoil has since 1996 been capturing, compressing and injecting, during natural gas extraction, about 1 million tonne of CO_2 per year into a deep saline aquifer off the shore of Norway (IEA, 2006).

is more relevant here. In pre-combustion the fuel is reacted with air or oxygen and then with steam to produce a mixture of CO_2 and H_2, of which the former is removed and the latter is used as the fuel. Pre-combustion is somewhat proven for PF (pulverised fuel) plants, but less so for IGCC (integrated gasification combined cycle) plants (IEA, 2007b). Therefore, both R&D and LbD are necessary in pre-combustion. Oxy-combustion uses oxygen instead of air and results in a flue gas consisting mainly of CO_2, and may lead to nearly zero GHG emissions after capture (IEA, 2007b). This method is at a relatively early stage of development and thus necessitates more R&D.

IEA (2006) states that the current costs of CCS applied to power generation are estimated at between \$40 and \$90 per tonne of CO_2 captured and stored depending on the power plant fuel and the technologies used. The bulk of the cost is on the capture side, with transport and storage costs ranging from 4 to \$12 per tonne of CO_2 (IEA, 2006; 2007b). The captured CO_2 can in some cases be used for enhanced oil recovery (EOR), or enhanced coal bed methane (ECBM) projects, which means that mitigation costs for such projects could be lower and in extreme cases negative (IPCC, 2005; IEA, 2006).

To carry out the numerical analysis in this paper, we apply a multi-period, partial equilibrium model for the global energy markets (Aune et al., 2005; 2009; Rosendahl and Sagen, 2009). By means of this model we investigate and compare two main policy scenarios. One scenario with an ambitious, international climate policy, and one scenario where this same climate policy is supplemented with considerable subsidies to CCS investments. We examine how the two policy scenarios may affect incentives to retrofit old power plants with CCS, and to invest in new plants with CCS, and how future energy prices are influenced by these policies. Different assumptions regarding current costs of CCS, learning rates for CCS technologies, and policies are considered[1].

The rest of the paper is structured as follows. In Section 1 we use a simple theoretical analysis to show how reductions in costs of CCS (either due to technological progress or subsidies) may affect energy prices. Section 2 presents the numerical model FRISBEE. In Section 3 we discuss the numerical results, and the last Section concludes.

1. Theoretical analysis

In our theoretical analysis we consider a partial equilibrium model of a closed competitive power market, consisting of five different technologies: gas power with (GC) and without (GP) CCS, coal power with (*CC*) and without (CP) CCS, and renewable power (RP).

First order conditions for power production of technology j are given by $MC^j = p^E$, where MC^j denotes marginal costs and p^E – the price of electricity. The supply of power by technology j can then be represented by a supply function S^j, which is the inverse function of the aggregated marginal cost function for all firms having technology j. Supply is a decreasing function of the input costs $p^i + \tau \cdot CO2^j$, where p^i denotes the input price of fuel i (i = gas (G), coal (C)) used by technology j, τ is the price of CO_2 emissions, and $CO2^j$ are the emissions per fuel use for technology j. Input costs are assumed to be zero for renewable power.

Let A^j be an exogenous factor so that $MC^j = A^j p^E$. This factor may either be interpreted as an ad valorem production subsidy (with $A^j > 1$), or as an exogenous technology index equal to all firms with technology j (an increase in A^j reduces MC^j/A^j and thus represents technological progress). Supply from technology j is then an increasing function of the electricity price p^E times the exogenous factor A^j. In the theoretical analysis we only consider changes in A^j for CCS technologies. To sum up, the power supply functions are given by

$S^j(p^i + \tau \cdot CO2^j, A^j p^E)$ with $S^j_{pi} < 0$ and $S^j_{pE} > 0$.

Let D denote the power demand function, which is decreasing in the price ($D_{pE} < 0$). Market equilibrium in the power market is then given by:

$$S^{GP}(p^G + \tau CO2^{GP}, p^E) + S^{GC}(p^G + \tau CO2^{GC}, A^{GC}, p^E) + S^{CP}(p^C + \tau CO2^{CP}, p^E) + \\ + S^{CC}(p^C + \tau CO2^{CC}, A^{CC} p^E) + S^{RP}(p^E) = D(p^E) \tag{1}$$

We normalise $A^j = 1$ initially.

Furthermore, supply of gas and coal (alternatively, supply minus demand in other sectors/countries) are given by the functions $S^i(p^i)$, which are increasing in p^i ($S^i_{pi} > 0$). We assume that there is a fixed conversion rate between fuel input and electricityoutput for each technology, given by α^j. This implies that $\alpha^j S^j_{p^E} = -S^j_{p^i}$, where S^i_p denotes the derivative of S^j with respect to p. Market equilibria in the gas and coal markets are then given by:

[1] It could be interesting to study the effects on CCS investments of other policy instruments too, such as other subsidy schemes for CCS, subsidies to renewable energy, and phasing out fossil fuel subsidies.

$$\alpha^{GP} S^{GP}(p^G + \tau CO2^{GP}, p^E) + \alpha^{GC} S^{GC}(p^G + \tau CO2^{GC}, A^{GC} p^E) = S^G(p^G), \quad (2)$$

$$\alpha^{CP} S^{CP}(p^C + \tau CO2^{CP}, p^E) + \alpha^{CC} S^{CC}(p^C + \tau CO2^{CC}, A^{CC} p^E) = S^C(p^C) \ . \quad (3)$$

In order to simplify the derivations below, we assume that coal prices are unaffected by changes in the power market, e.g., due to a horizontal supply function[1]. We also assume that the CO_2 price and the technology-specific emission rates are fixed. Fuel and electricity units are normalised so that $\alpha^{GP}= 1$, which means that ($\alpha^{GC} - 1$) denotes the extra gas needed to produce the same quantity of electricity when CCS is used.

What are the effects of exogenous increases in A^{GC} and A^{CC}, i.e., either subsidies to production of power with CCS, or technological progress for CCS technologies? The effects in the power market and the gas market are found by totally differentiating equations (1) and (2):

$$\begin{aligned} & S^{GP}_{p^G} dp^G + S^{GP}_{p^E} dp^E + S^{GC}_{p^G} dp^G + S^{GC}_{p^E} (dp^E + p^E dA^{GC}) + \\ & + S^{CP}_{p^E} dp^E + S^{CC}_{p^E} (dp^E + p^E dA^{CC}) + S^{RP}_{p^E} dp^E = D_{p^E} dp^E , \end{aligned} \quad (4)$$

$$S^{GP}_{p^G} dp^G + S^{GP}_{p^E} dp^E + \alpha^{GC}\left(S^{GC}_{p^G} dp^G + S^{GC}_{p^E}\left(dp^E + p^E dA^{GC}\right)\right) = S^G_{p^G} dp^G . \quad (5)$$

There are two endogenous variables in equations (4) and (5), i.e., dp^G and dp^E. By using Kramer's rule, we get:

$$dp^G = \frac{p^E S^{GC}_{p^E}\left(S^{GP}_{p^E} + \alpha^{GC} S^{GC}_{p^E} - \alpha^{GC}\Phi_{p^E}\right)}{\Delta} dA^{GC} + \frac{p^E S^{CC}_{p^E}\left(S^{GP}_{p^E} + \alpha^{GC} S^{GC}_{p^E}\right)}{\Delta} dA^{CC} , \quad (6)$$

$$dp^E = \frac{p^E S^{GC}_{p^E}\left[S^G_{p^G} + S^{GP}_{p^G}\left(\alpha^{GC} - 1\right)\right]}{\Delta} dA^{GC} - \frac{S^{CC}_{p^E} p^E \left(S^{GP}_{p^G} + \alpha^{GC} S^{GC}_{p^G} - S^G_{p^G}\right)}{\Delta} dA^{CC} \quad (7)$$

where[2]

$$\Delta = \left(\Phi_{p^E} - S^{GP}_{p^E} - \alpha^{GC} S^{GC}_{p^E}\right) S^{GP}_{p^G} + \left(\alpha^{GC}\Phi_{p^E} - S^{GP}_{p^E} - \alpha^{GC} S^{GC}_{p^E}\right) S^{GC}_{p^G} - \Phi_{p^E} S^G_{p^G} < 0$$

and

$$\Phi_{p^E} = S^{GP}_{p^E} + S^{GC}_{p^E} + S^{CP}_{p^E} + S^{CC}_{p^E} + S^{RP}_{p^E} - D_{p^E} > 0 .$$

The price effects clearly depend on whether or not both A^{GC} and A^{CC} are increased, and the relative increases of the two factors. Assume first that $dA^{GC} > 0$ and $dA^{CC} = 0$, so that only gas power with CCS is stimulated through technological progress or targeted subsidies. Consider first the sign of dp^G. This is definitely positive, as the numerator in front of dA^{GC} in equation (6) is negative (cf. the expression for Φ_{pE}). This is as expected – increased profitability of gas power with CCS increases the demand for gas, raising the gas price.

The sign of dp^E is actually ambiguous, and depends on the supply elasticity of gas, the efficiency loss of using CCS in gas power plants, and the price elasticity of conventional gas power (cf. equation (7)). If the efficiency loss of CCS were negligible, we see that the electricity price would fall, which we typically expect when a power technology is subsidized. However, if gas supply is almost fixed (S^G_{PG} is small) and the efficiency loss of CCS is substantial ($\alpha^{GC} > 1$), technological change in gas power with CCS may lead to *higher* electricity prices. The explanation is that increased use of gas power with CCS reduces the supply of conventional gas power due to higher gas prices, and total power production can then be reduced as gas power with CCS delivers less power than conventional gas power, given the same amount of fuel input. This ambiguity is confirmed in the simulations below, where we find somewhat mixed results for dp^E.

[1] For an individual region such as Europe, it seems fair to assume a horizontal supply function for coal but not for gas. On a global scale the assumption is less realistic, although in the medium to long-run we believe the supply function for coal to be relatively flat (see, e.g. Aune et al., 2008). In the numerical simulations with the FRISBEE model below, the coal supply function is moderately sloping upwards, see Figure 2.

[2] $\Delta < 0$ follows from the observation that the sum of the two first terms are less than $\left(-(\alpha^{GC})^2 + 2\alpha^{GC} - 1\right) S^{GC}_{p^E} S^{GP}_{p^E} < 0$ (because $\alpha^{GC}>1$). Here we have also used that $\alpha^j S^j_{p^E} = -S^j_{p^G}$.

A possibly positive price effect for electricity would have some interesting implications. First, it would imply that production of renewable power increases as a consequence of increased profitability of CCS. Second, because total electricity demand falls when the price increases, total gas power production, i.e., with or without CCS, must decrease (as both coal power and renewable power increase production due to the higher power price).

Assume now that also $dA^{CC} > 0$. The fraction in front of dA^{CC} in equation (7) is definitely negative. Therefore, subsidies to coal power with CCS, or technological progress for this technology, has a negative effect on the electricity price. This follows because coal prices are fixed in this model, which means that conventional coal power production is not reduced unless the electricity price falls. The higher is dA^{CC} compared to dA^{GC}, the more unlikely it is that p^E increases.

What about dp^G? Now the sign in equation (6) is ambiguous, as the term in front of dA^{CC} is negative. Obviously, the more coal power with CCS reacts to a negative shift in costs of delivery (i.e. the larger S^{CC}_{pE} is), the larger is this term, and, correspondingly, the more gas power with CCS reacts to a negative shift in costs of delivery (i.e., the larger S^{GC}_{pE} is), the larger is the term in front of dA^{GC}. We conclude that subsidies or technological progress for CCS technologies have ambiguous impacts on natural gas prices, particularly depending on the relative sizes of dA^{GC} and dA^{CC}, and the price responsiveness of supply of the two CCS technologies when costs of supply are reduced[1]. This ambiguity is also found in the numerical simulations below.

2. FRISBEE – a model of international energy markets

In the numerical analysis we use the FRISBEE model, which is a recursive, dynamic partial equilibrium model of the international energy markets, with one year period length[2]. Supply and demand of fossil fuels and electricity are modelled in 13 global regions, cf. Table 1. The model accounts for discoveries, reserves, field development and production of oil and natural gas in each region. Coal production is also modelled explicitly in each region, but in a simpler way. The power sector demands fossil fuels, and transforms them into electricity. Production of electricity is based on already installed capacities, which are modelled endogenously (see below). There are two end-user sectors in the model: 'manufacturing industries' and 'others' (including household consumption). The base year of the model is 2000, and it is programmed in GAMS (Brooke et al., 2005).

Table 1. Regions in the FRISBEE model

Industrialised regions	Regions in transition	Developing regions
Canada	Caspian region	Africa
OECD Pacific	Eastern Europe	China
USA	Russia/Ukraine/Belarus	Latin America
Western Europe		OPEC-Middle East
		Rest-Asia
		OPEC-Africa

End-user demand for any energy good depends on the end-user prices of all energy goods. The exogenous parameters population growth, income growth and energy efficiency also affect end-user demand in the model. Towards 2050 per capita income growth for the individual regions is assumed to approach each other with a mean growth around 2.5 per cent per year in the long run. The direct price elasticities for the end-user sectors vary mostly between -0.1 and -0.4 in the long run, and between -0.03 and -0.2 in the short run. Cross-price elasticities are in general smaller. Per capita income elasticities vary a lot, from negative elasticities for coal in Western Europe to above one for natural gas in several regions.

In FRISBEE, fossil fuels are traded between regions, whereas electricity is only traded *within* each region. Oil and coal trade take place via a common pool, whereas gas trade takes place bilaterally due to larger transport costs (Rosendahl and Sagen, 2009). The gas and coal markets are assumed to be competitive, with no formal link from oil to gas prices (as in many traditional gas contracts). In the oil market, OPEC's market power is taken into account (cf., Aune et al., 2005)[3].

Extraction of oil and gas in FRISBEE is based on running production capacities, marginal operating costs and regional producer prices. Investments in exploration, field development and reserve extensions are driven by expected returns, based on adaptive price expectations, and unit operating and capi-

[1] Note that targeted research into gas power with CCS could have negative impacts on gas prices if there are spillover effects between different CCS technologies, so that both A^{GC} and A^{CC} are increased.

[2] See, Aune et al. (2005; 2009) and Rosendahl and Sagen (2009) for a more extensive presentation of the FRISBEE model. The model description in the current paper focuses mostly on the power market, which is particularly important in our analysis.

[3] In the current analysis, however, the oil price path is held constant in real terms at $US\$_{2007}$ 47 per barrel in all scenarios (from 2010), with OPEC being the residual supplier. Although this is a simplification, it has negligible influence on the results in this paper. There are no investments in oil power plants in any scenario at this price level, which most likely is an underestimation of the future oil price level. Thus, varying the oil price would only affect the utilisation rate of existing oil power capacity. Given the small share of oil power in global power production (falling from 7 to 3 per cent in our *Reference Scenario*), and the small share of global oil production going to the power sector (falling from 9 to 3 per cent), the results would have been approximately the same with a more realistic modelling of the oil price.

tal costs. Production of coal is based on total marginal extraction costs (i.e., including capital costs) and regional prices (production capacities are not explicitly modelled).

FRISBEE accounts for production in 9 endogenous and 6 exogenous power technologies (see table 2). Four of these include carbon capture and storage (CCS), either as a post-combustion technology ("post-CCS") or as an integrated technology ("pre-CCS"). For the endogenous technologies, power production is based on installed capacities, while investment in new capacity adds to total production capacity in future years. Production of electricity from the endogenous technologies depend on the price of electricity, the price of energy input (except for wind power), the price of carbon emissions, fuel efficiency (conversion rate), and operating costs. For CCS power plants, costs of transport and storage of CO_2 also matter. Because electricity produced from different technologies are perfect substitutes, the least-cost technologies will always be chosen. Thus, substitution possibilities between fossil fuels are much higher here than in the two end-user sectors. For the exogenous technologies, future power production is projected based on e.g. EIA (2008).

Table 2. Power technologies in the FRISBEE model

Endogenous technologies	Learning rate included?	Exogenous technologies
Gas power	No	Nuclear power
Gas power with post-CCS	Yes	Hydropower
Gas power with pre-CCS	Yes	Solar power
Coal power	No	Lignite power
Coal power with post-CCS	Yes	Waste power
Coal power with pre-CCS	Yes	Other renewable power
Oil power	No	
Bio power	Yes	
Wind power	Yes	

As in the gas and oil producing sectors, investments in new power capacities are driven by expected returns. Net present values are calculated for the different power technologies in different regions, based on adaptive expectations for fuel prices, carbon emissions prices and electricity prices[1], a pre-specified required rate of return (we assume a real rate of 10 per cent), and cost elements such as investment costs and operating/maintenance costs. There is a time lag between investment decision and production start-up, which varies across technologies (from one year for wind power to six years for coal power with pre-CCS). In the short run, unit capital costs are assumed to be an increasing function of the amount of investments within the same technology and/or within the same region, as accelerated construction of new plants tends to push up construction costs. In the long run, we assume there are learning potential in non-mature technologies such as CCS, wind and bio power, driving down their capital costs. Based on IEA (2006) and Rao et al. (2006), global learning rates are assumed to be 5-7 per cent for wind and bio power and 13 per cent for CCS technologies in the main scenarios. We also consider more optimistic learning rates for CCS in some sensitivity scenarios. A learning rate of x per cent means that unit investment costs for a technology fall by x per cent for every doubling of accumulated global production capacity of this specific technology. Costs and efficiencies of different power technologies (including CCS) are based on various sources (Aune et al., 2008; IEA, 2005; MIT, 2007; Riahi et al., 2004; Rubin et al., 2007).

Efficiency of existing plants varies a lot across regions. For new plants, however, we assume that state of the art technologies are used, gradually increasing the average efficiency of the installed capacity. This may be a too optimistic assumption for some regions, but it shouldn't affect our main results. In addition to building new coal or gas plants with CCS, we also allow for retrofitting old plants with post-CCS technologies. Investment decisions for post-CCS are similar to the ones for new plants, except that the relevant present value here is the difference in profitability before and after retrofitting.

Regional costs of wind and bio power are negatively affected by global learning effects, but positively affected by regional resource scarcity. That is, we assume that the best remaining wind locations within a region are always chosen first (when profitable). The same applies to supply of bio mass, which leads to a bio supply function that increases with the price of bio mass (bio power plants also compete with other users of bio mass, or other crops that can be cultivated at the same location, implying a price sensitive supply function). Initially, learning effects are in general more important than scarcity effects for both wind and bio, but when wind and/or bio power matures, the scarcity effects dominate. Regional wind potentials are based on Archer and Jacobson (2005), de Vries et al. (2007) and Aune et al. (2008), whereas bio supply potentials and costs are based on Haq (2002) and de Vries et al. (2007).

[1] Adaptive price expectations may lead to volatile price changes in the product markets and investment decisions may turn out to be (very) unprofitable ex post. In FRISBEE investors use the mean price of the last 6 years to form their price expectations, which tends to reduce the price volatility compared to price expectations based on near past prices. A pre-specified real rate of return of 10 per cent, which is much higher than e.g. the yield achieved from investing in long-term US Treasury Bonds (see e.g. http://fixedincome.fidelity.com/fi/FIHistoricalYield which suggests a mean real interest rate of 4.5 per cent for 30-year US Treasury Bonds), should provide investors ample incentives to invest in energy production and extraction, even in the presence of substantial energy price volatility. We do not model, however, the impacts of price volatility as such on investments.

There are a lot of uncertainties about current and future costs and efficiencies of different power technologies around the world, not least CCS technologies. Consequently, we run several sensitivity analyses where crucial assumptions related to carbon capture are changed.

3. Numerical simulations

3.1. Scenario description. We consider three main scenarios in this paper: one reference scenario plus two alternative scenarios (see Table 3). The *Reference Scenario* is referred to as one, where all Annex B countries excluding the US impose a CO_2 tax of 10 US$_{2000}$ per tonne of CO_2, starting from 2008 and remaining valid throughout our model horizon. The choice of this scenario as a reference one is because it is close to the current situation with the Kyoto Protocol prolonged into the future. Thus, it serves well as a benchmark scenario for our comparison analyses.

Table 3. Scenario description

Scenario name	Scenario description
Reference scenario	Constant CO_2 tax of 10 US$_{2000}$ per tonne in Annex B (excluding the US)
Alternative scenario I	Global CO_2 tax rising linearly from 26 US$_{2000}$ in 2013 to 100 US$_{2000}$ in 2050
Alternative scenario II	Same CO_2 tax as in *Alternative scenario I*, and a 75 per cent subsidy to the overnight cost when investing in CCS technologies

Note: Overnight construction costs include owner's cost, EPC (engineering, procurement and construction) and contingency, but exclude interests during construction (IDC), see IEA (2010, 22, footnote 5).

Both alternative scenarios assume a global effort to address the climate change problem after the Kyoto rotocol expires at the end of 2012. *Alternative scenario* I departs from the *Reference scenario* in that the afore-mentioned CO_2 tax is replaced by a global tax in 2013. This new CO_2 tax increases linearly from 26 US$_{2000}$ per tonne of CO_2 in 2013 to 100 US$_{2000}$ per tonne in 2050. Although other scenarios may be viewed as more realistic, the intention of *Alternative scenario* I is to examine the impacts of increased CO_2 tax, both in depth (in terms of the ascending values) and in scope (in terms of more regions conducting the tax), on the incentives to invest in power plants with CCS technologies, and the subsequent effects on energy prices. *Alternative scenario* II is built on *Alternative scenario* I. In addition to the CO_2 tax imposed, substantial capital cost subsidies when investing in CCS technologies are introduced in the model from 2013. This is implemented with a subsidy to overnight costs. All other cost elements are not subsidized. The subsidy rate is initially set to 75 per cent, but we also report the results of other subsidy levels. Note that investing in CCS technologies also involves other extra costs, such as reduced efficiency and higher operating costs. The purpose of this alternative scenario is to investigate the effects on energy prices and market shares in the power market of implementing such targeted subsidies, which may be introduced as supplements to a price on emissions in order to hasten the introduction of carbon capture.

3.2. Reference scenario. We start by briefly presenting the *Reference scenario*, as it develops from 2010 to 2050. Note that this is not a projection of the future, but a benchmark scenario for examining potential effects of different policies. Moreover, the further into the future we look, the more uncertainty there is about income growth, demand conditions and costs of different (especially emerging) technologies.

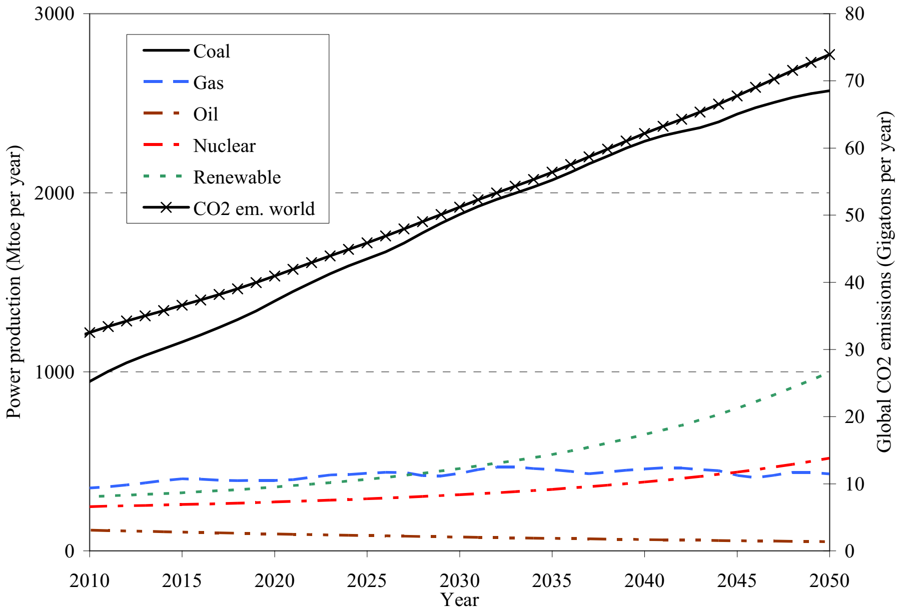

Fig. 1. Global power production (Mtoe) from different technologies and global CO_2 emissions (Gigatons) per year. Reference scenario.

As shown in Figure 1, without any climate policy beyond current policies, worldwide coal power production increases considerably. Its market share grows from around 40 per cent in 2000 to around 55 per cent in 2050. Due to high gas prices (see below), gas power production grows only slowly, whereas oil power production declines as existing capacity is phased out. By assumption, nuclear power production grows moderately. Obviously, there is no power production with CCS without new policies. Renewable power production grows by around 2 per cent per year despite any climate or renewable policies with almost 10 per cent annual growth for the two endogenous technologies wind and bio power[1].

Global CO_2 emissions almost triple from 2000 to 2050, showing the tremendous task of trying to reduce emissions from current levels. Global emissions from the power sector increase by 150 per cent in the same period, and constitute one third of total emissions in 2050. Total emissions in OECD double in these 50 years, and emissions in Former Soviet Union almost double. Total emissions in the rest of the world increase by more than a factor of 4[2].

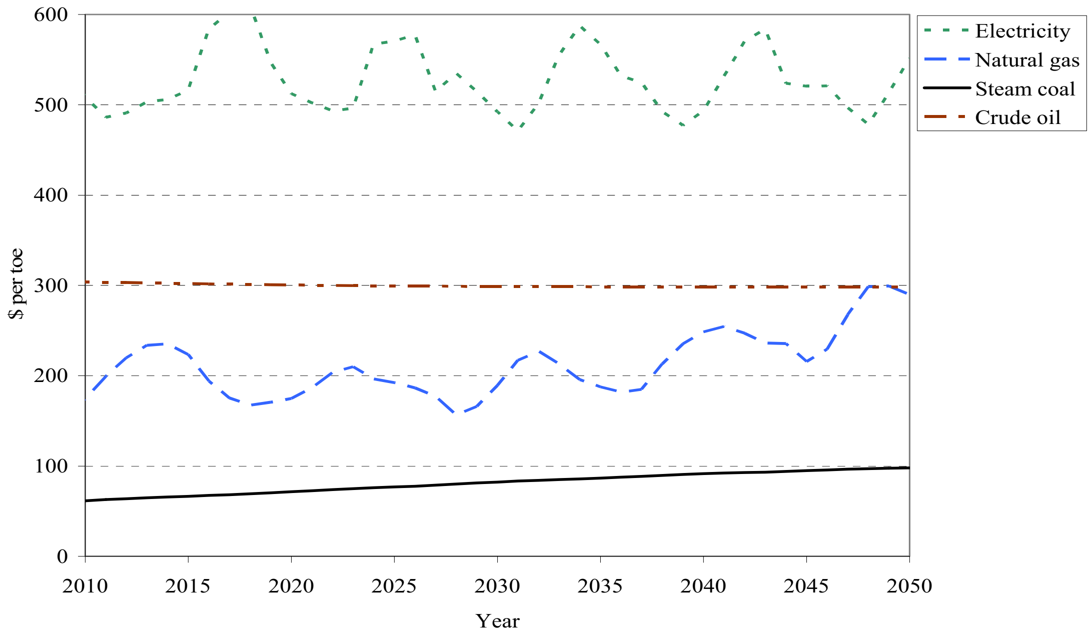

Fig. 2. Global mean energy prices. Reference scenario. US$$_{2000}$ (per toe)

The initial price of steam coal is substantially below the price of natural gas (see Figure 2), which explains the strong growth for coal power and slow growth for gas power seen in Figure 1. However, the large increase in coal demand pushes coal prices upwards and reduces the price differential between gas and coal until 2030. The rising price trend for natural gas after 2030 is due to the fact that depletion of the least expensive gas fields makes remaining gas resources more costly to develop. Notice that the prices of gas (and electricity) have a tendency to over and under shoot, which is due to the assumption of adaptive price expectations.

Interestingly, the price of electricity does not rise notably over this time horizon, despite increased prices of coal and natural gas. There are two reasons for that. First, coal power production is still profitable at higher coal prices and unchanged electricity prices in 2050, which is partly due to increased average efficiency in coal power plants. Initially, investment growth is dampened because marginal investment costs increase if the capacity growth is too rapid. Second, wind and bio power expand considerably, and obtain significant market shares in the last couple of decades. The gradual production growth is again due to the fact that rapid expansion (relative to existing capacities) is costly, but also partly due to cost reductions following learning by doing effects .

3.3. Alternative scenarios. Next, we consider the two policy scenarios, i.e., *Alternative scenarios* I-II. We are particularly interested in what effects the policies have on the expansion of CCS technologies, and how energy prices and market shares are affected. Note that, unless otherwise specified, when we refer to coal or gas power production, we mean production from both conventional plants and plants with CCS installed.

[1] Note that this development in the power sector is only based on profitability considerations for the endogenous technologies, assuming equal costs of the same technology around the world. Any barriers to e.g. wind power investments in developing countries or coal power production in developed countries are ignored. For the exogenous renewable technologies, some growth in power production is assumed towards 2050.

[2] The growth in CO_2 emissions in our baseline scenario lies in the upper-end of other long-term scenarios, especially for OECD (IPCC, 2007; EIA, 2008). This is due to the low extraction costs and large reserves of coal, which makes coal very competitive compared to other energy sources in the long run (see also the preceding footnote). The A1F scenario outlined by the IPCC, with large and cheap access to fossil fuels, has even higher CO_2 emissions than our baseline scenario in 2050.

Consider first *Alternative scenario* I, which is a quite ambitious climate policy scenario with a global price on CO_2 from 2013. We see from Figure 3 that the effects on global power prices are significant. In the period of 2020-2040, producer prices are 35-65 per cent higher than in the *Reference scenario*[1]. At the end of our time horizon, the price increase is less pronounced as more renewable power production is phased in (see below).

A price on CO_2 reduces the demand of coal, the most carbon-intensive fossil fuel. Consequently, the global mean price of coal falls considerably compared to the *Reference scenario*, cf. Figure 4. Natural gas is the least carbon intensive fossil fuel, and the effects on gas prices are initially mixed (see Figure 5). In the long term, gas prices seem to increase as gas power is stimulated by the climate policy (see below). Consumption of gas in other sectors, on the other hand, is reduced as substitution possibilities towards gas from other fossil fuels are fewer than in the power sector.

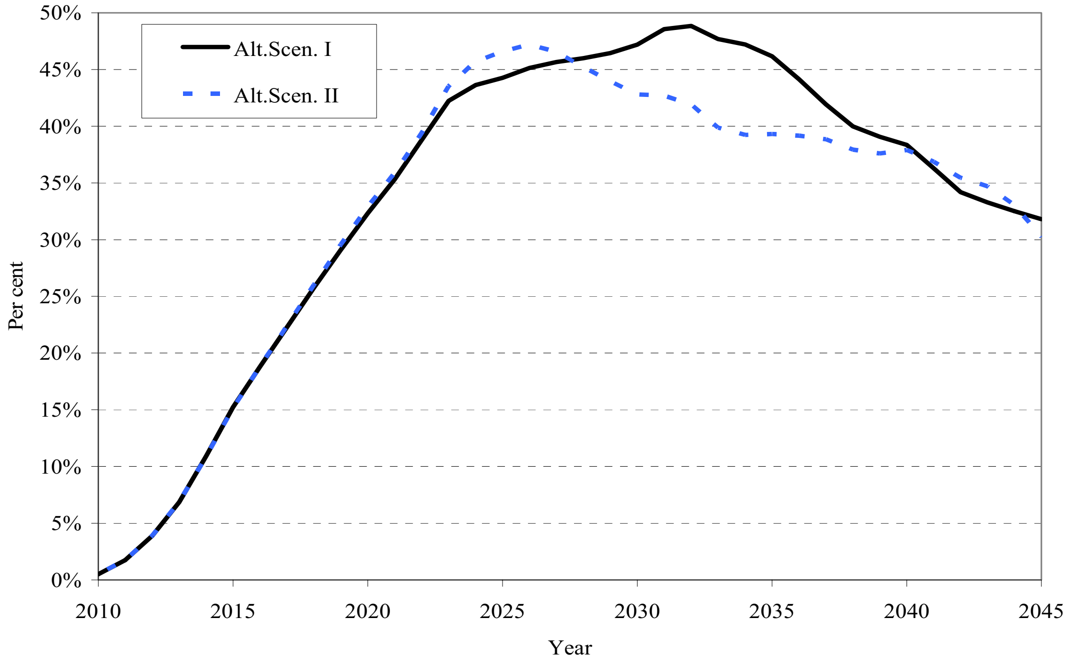

Fig. 3. Global mean electricity prices (percentage change from Reference scenario)

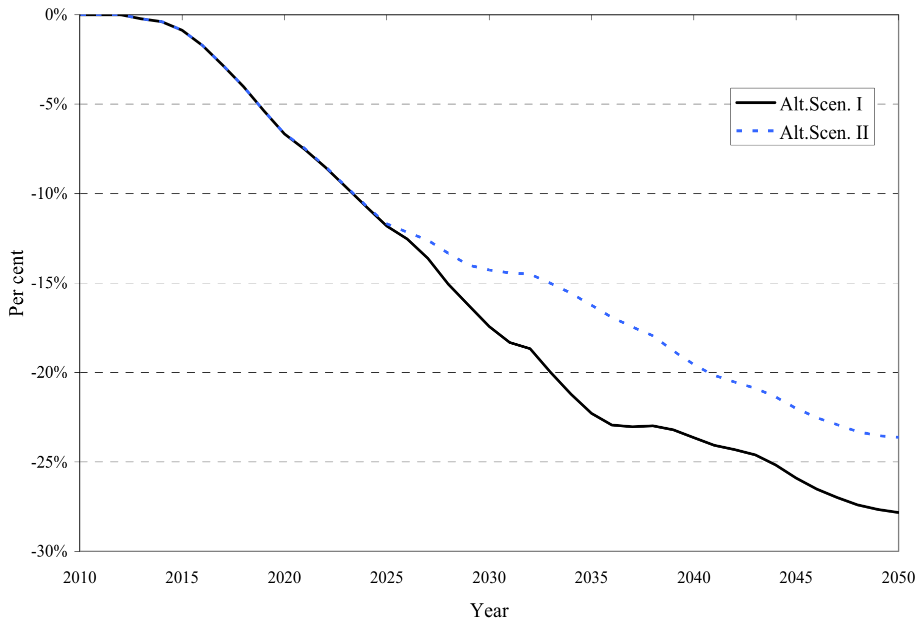

Fig. 4. Global mean steam coal prices (percentage change from Reference scenario)

[1] Note that the electricity and gas prices shown in Figures 3 and 5 are 10-year average prices. The reason is that the recursive modelling with adaptive price expectations leads to significant price cycles for these two energy goods (cf. Figure 2). Thus, 10-year average prices provide a better comparison of price effects in different scenarios. Note also that all Figures show effects on *producer* prices (i.e., the prices power producers get), not *end-user* prices. Percentage effects on end-user prices will in general be lower, as they typically also include distribution costs and taxes.

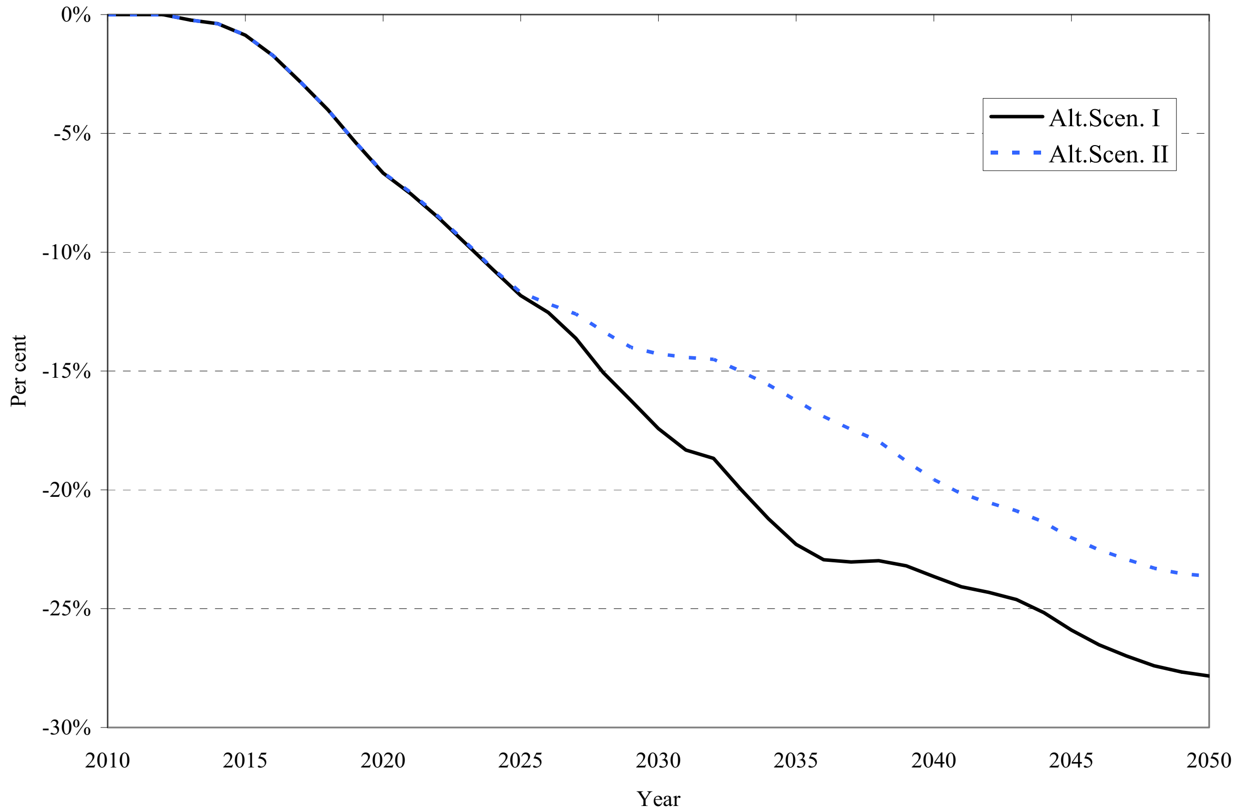

Fig. 5. Global mean natural gas prices (percentage change from Reference scenario)

The climate policy imposed in *Alternative scenario* I has substantial effects on the market shares in the power market. In particular, investments are shifted towards less carbon-intensive energy inputs. Previously installed capacity, however, is still profitable to run in most cases, and so market shares shift only gradually.

As seen in Figure 6, coal power production grows very little after 2013, compared to a hefty growth in the *Reference scenario*. New investments in coal power are substantially reduced. *Conventional* coal power production (without CCS) peaks just before 2030, and is reduced by 75 per cent in 2050 as a major share of coal power plants is equipped with carbon capture.

Coal power is partly substituted by gas power – global gas power production increases as a consequence of the price on CO_2, cf. Figure 7. However, less than 10 per cent of the reduction in coal power supply caused by the climate policy is replaced by gas power. After 2040, a substantial increase in renewable power supply dampens the increase in electricity prices, and investments in new gas power plants are depressed. This illustrates how climate policy is a double-edged sword for gas power plants. Moderate or short-lived climate policies will most likely benefit natural gas as its main competitor is coal, whereas strong and long-lived climate policies may have opposite effects as CO_2-free alternatives become more competitive. *Conventional* gas power production peaks around 2030, and drops by around two thirds towards 2050.

Figure 8 shows how renewable power production eventually escalates when a global price on CO_2 is introduced. Between 2020 and 2050, when power prices have increased and investments have started to kick-off, production of wind and bio power grows by 10-11 per cent per year on average. In 2050, renewable power has a market share of almost 50 per cent, compared to around 15 per cent in 2013.

The CO_2 price gradually makes carbon capture profitable, even without any subsidies (see "0% (Alt. Scen. I)" in Figure 9). After 2030, when the CO_2 price has reached 60 $US\$_{2000}$ per ton, CCS equipment is installed on a large number of existing coal and gas power plants. In addition, a small amount of new gas and coal power plants with carbon capture is built. By 2040, 15 per cent of all power production comes from CCS plants, and by 2050 the share has doubled. A large majority of coal and gas power plants are then CCS plants. Carbon capture is mostly installed in coal power plants, especially when the growth accelerates after 2035. Towards the end of our time horizon, however, the share of gas power plants that are retrofitted with CCS increases as the number of conventional coal power plants is significantly reduced.

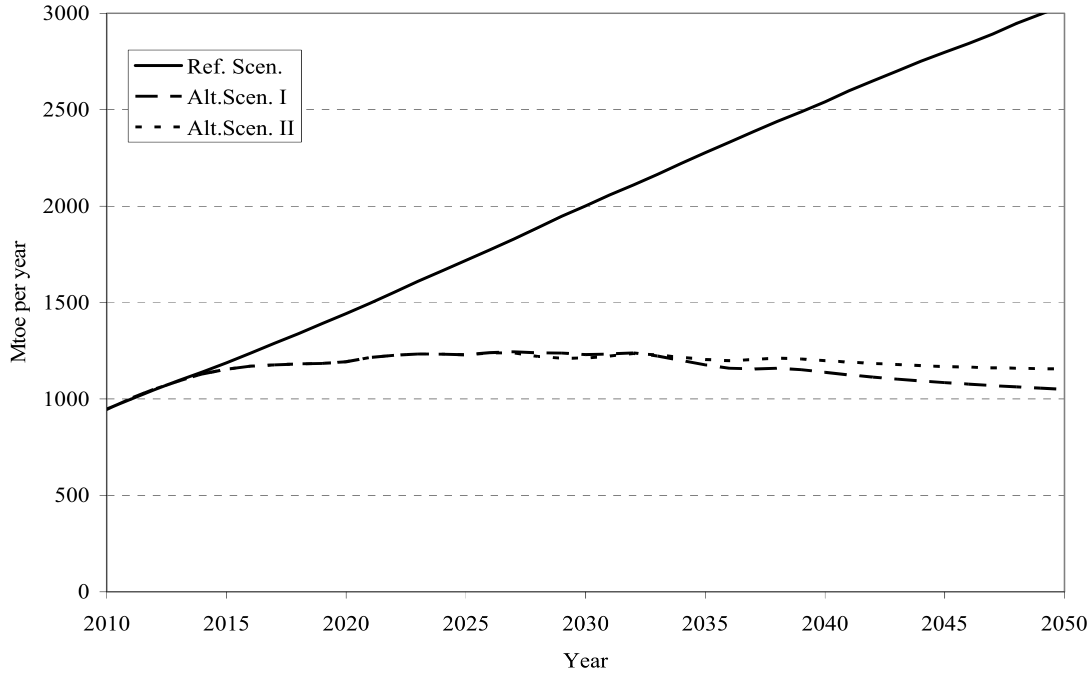

Fig. 6. Global production of coal power (including plants with CCS), Mtoe per year

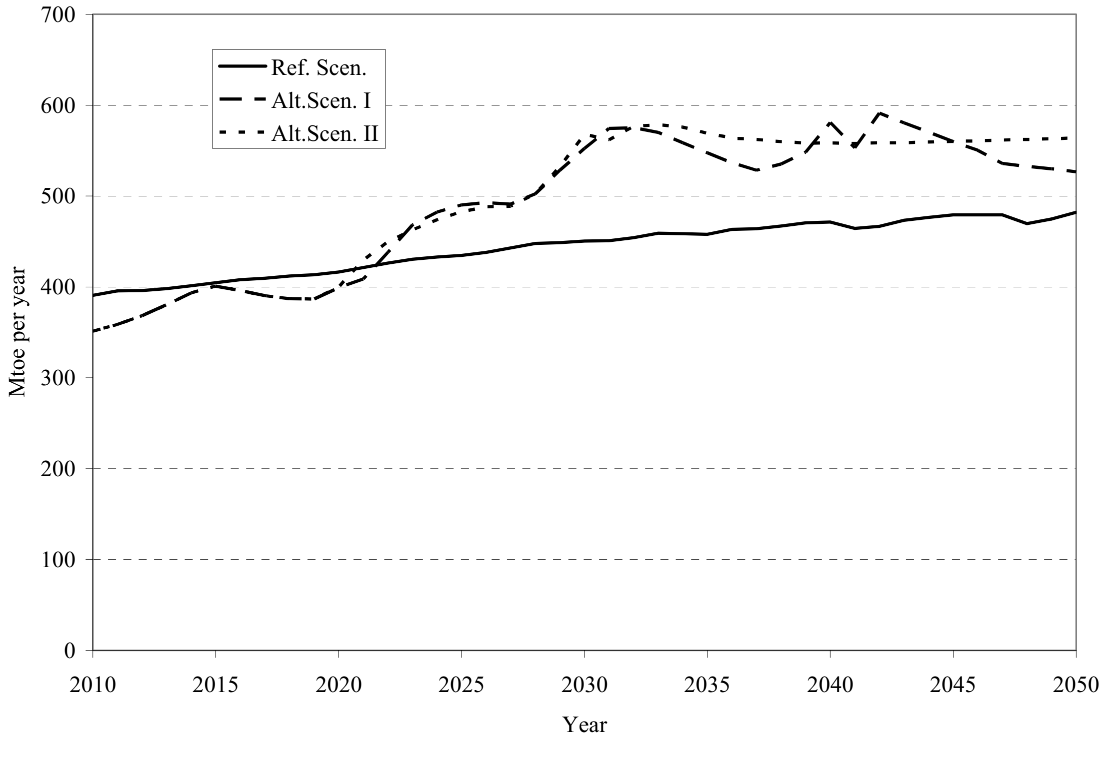

Fig. 7. Global production of gas power (including plants with CCS), Mtoe per year

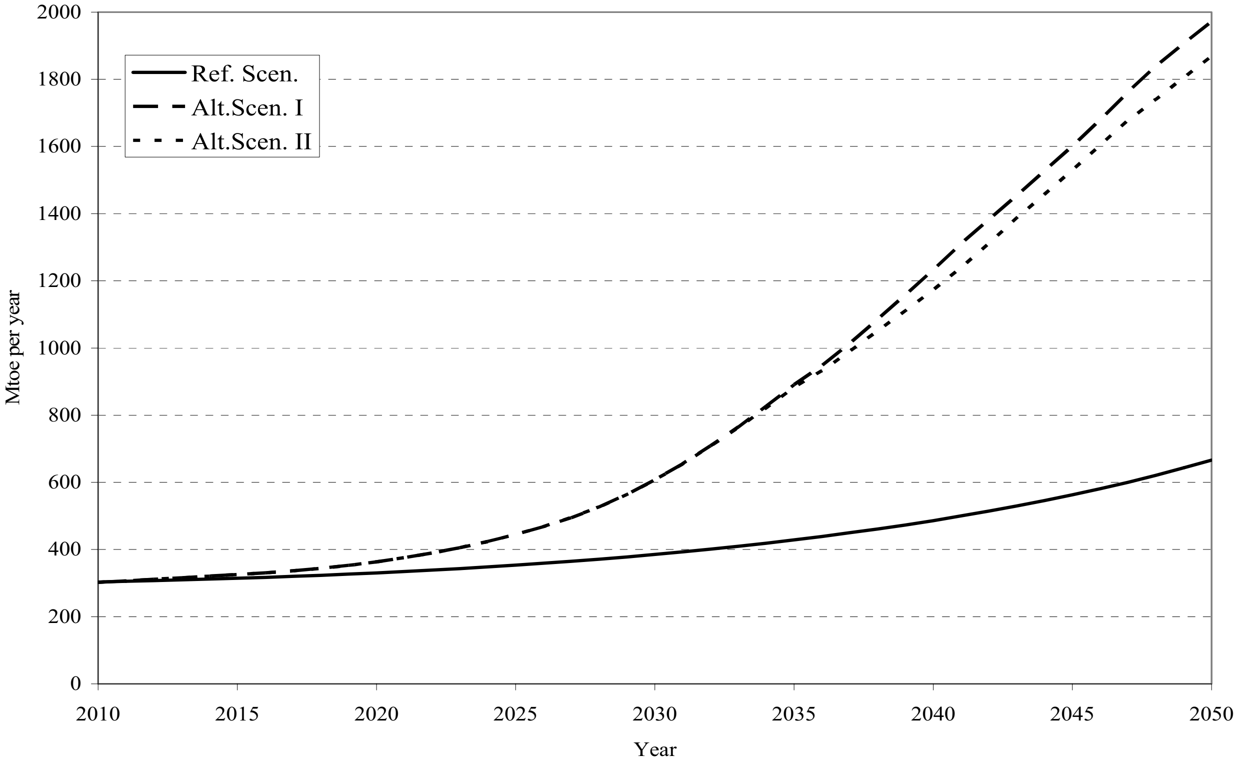

Fig. 8. Global production of renewable power, Mtoe per year

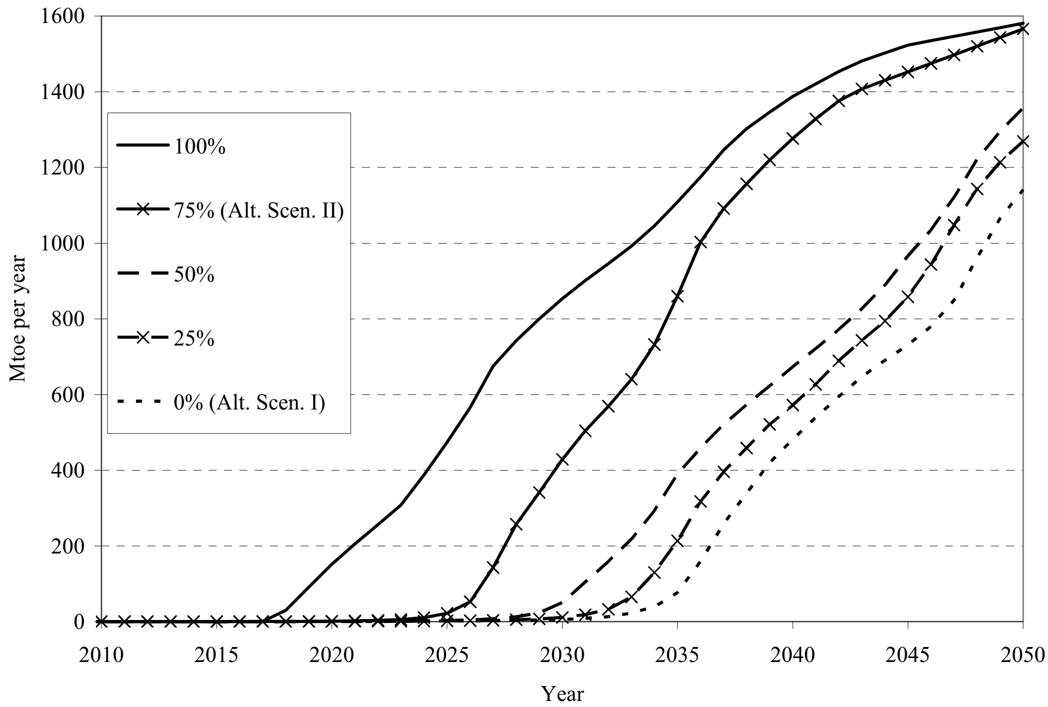

Fig. 9. Global power production with CCS, Mtoe per year

Figure 10 shows that global emissions of CO_2 are significantly reduced in *Alternative scenario* I compared to the *Reference scenario*, especially after 2030 when CCS is phased in and renewable power production captures significant market shares. Still, emisions continue to rise somewhat, which indicates that even stronger climate policies are needed in order to curb global emissions of CO_2. Emissions in the power sector are considerably reduced after 2030, but emissions in other sectors, where substitution possibilties are less, still increase to a large extent due to economic growth[1].

[1] This conclusion should be cautioned as the model does not take into account alternatives to fossil fuels and electricity except in the power sector (for instance a shift to electric or hydrogen driven cars in the transportation sector).

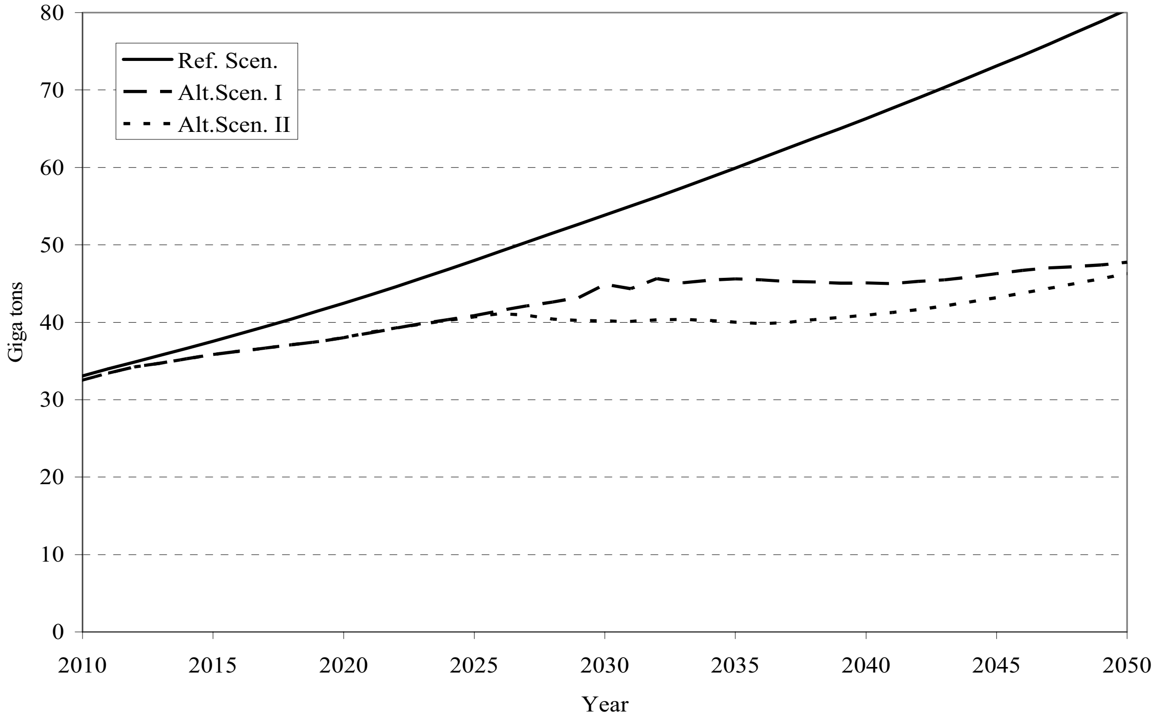

Fig. 10. Global emissions of CO_2

Next, we are interested in how subsidies to CCS investments may affect the power sector (*Alternative scenario* II). First, let us look at how it influences the deployment of CCS. This is shown in Figure 9, which also shows the results of alternative subsidy rates. We see that subsidising CCS investment costs by 75 per cent accelerates the use of CCS substantially. Furthermore, the Figure indicates that going from no subsidy to 50 per cent subsidy has less of an impact than increasing the subsidy from 50 to 75 (or 100) per cent (remember that CCS plants also have higher operating costs and lower efficiency). A 50 per cent subsidy advances the expansion of CCS by merely 3-4 years, whereas a 75 per cent subsidy advances it by at least ten years.

Intuitively, it is tempting to assume that CCS subsidies should increase total production of coal and gas power, reduce electricity prices and increase coal and gas prices. However, as shown in Section 2, effects on energy prices and market shares are in general ambiguous. This is also confirmed by the numerical simulations, as the results vary over time. In Figure 3 we see that subsidising carbon capture have mixed impacts on electricity prices (compared to *Alternative scenario* I). The same is true for gas prices (Figure 5), whereas coal prices are consistently increased by the subsidy (Figure 4).

The effects on power production are in line with the price effects. Total supply of coal power increases as a consequence of the CCS subsidy, but only moderately (Figure 6). The effect on total gas power production is mixed (Figure 7), and the same applies to total power production. The explanation is the following.

When carbon capture is subsidised, a large amount of existing coal and gas power plants are equipped with CCS technology. In comparison, few new plants with CCS are built. Thus, instead of stimulating gas and coal power investments (with CCS), the subsidy mainly changes the emission intensity and efficiency of the existing plants. This has two opposing effects. On the one hand, reduced emissions make the plant more profitable, and hence increases the lifetime of the plant. This is especially relevant for coal power plants, as coal has higher emission factor than gas. On the other hand, reduced efficiency means that more fuel is required to produce the same amount of electricity. Thus, the demand for coal and gas from the power sector increases even if coal and gas power production is unchanged. This leads to higher prices of gas and coal, making existing plants less profitable and depressing investments in new capacity. In addition, substantial investments in CCS increase the costs of conventional coal and gas power investment somewhat (a slight crowding out effect).

The small impacts on electricity prices imply that renewable production is only slightly affected by the CCS subsidy, at least until the last decade (Figure 8). Its market share in 2040 (2050) is reduced from 36 (48) to 35 (45) per cent because of the subsidy. When at the same time the market share of CCS increases from 14 (28) to 38 (38) per cent (Figure 9), it is fair to conclude that CCS subsidies will not threat the growth in renewable power production. Subsidising CCS has significant effects on global CO_2 emissions, at least temporarily (Figure 10). In 2030-35 global emissions are 10-12 per cent lower than in *Alternative scenario* I. However, in 2050 emissions are only three per cent lower, as CCS is being installed in large amount even without the subsidy (see above).

3.4. Sensitivity analyses. The results in *Alternative scenario* II may seem somewhat surprising, and thus call for extensive sensitivity analyses. In this subsection we therefore present the results of making significant changes in some crucial assumptions related to CCS. The results of the different sensitivity analyses are summarised in Table 4, where we report percentage changes in prices and production over the period of 2020-2050, compared to *Alternative scenario* I[1]. Figure 11 shows how CCS utilisation develops in the different sensitivity analyses under *Alternative scenario* II[2].

Table 4. Results from sensitivity analyses percentage changes from *Alternative scenario* I

Sensitivity analyses	Time period	Coal power	Gas power	Renewable power	Coal price	Gas price	Electricity price
Main scenarios (Alt. scen. II)	2020-2050	3.0%	1.3%	-3.3%	4.1%	-1.5%	-1.5%
S1. Higher efficiency of CCS plants	2020-2050	3.0%	-0.8%	-1.3%	3.5%	2.1%	-1.7%
S2. Higher initial costs of CCS	2020-2050	3.9%	0.3%	-2.5%	5.1%	8.3%	-2.4%
S3. Higher learning rates of CCS	2020-2050	2.4%	-0.6%	0.3%	3.6%	8.2%	-0.3%
S4. Higher costs of retrofitting CCS	2020-2050	3.5%	-0.7%	-1.7%	5.0%	7.8%	-2.1%
S5. CCS subsidy only in OECD	2020-2050	2.2%	2.2%	-2.2%	3.7%	-1.9%	-1.3%

Notes: In scenario S1 the efficiency losses compared to plants without CCS are reduced by 50%. In scenarios S2 and S4 the initial costs of respectively CCS and retrofitting CCS are increased by 50%. In scenario S3 the learning rates for CCS are increased by 50%.

The sensitivity analyses seem to confirm that total coal power supply and coal prices increase as a result of subsidizing CCS. The results for gas power production and natural gas prices are mixed, as we also noticed in Figures 5 and 7. Gas prices do however increase quite much in some scenarios. In these scenarios the increased demand for gas from gas power plants (retrofitted) with CS really drives up the natural gas price, even though total gas power supply is almost un-changed. The average electricity price is decreased by the CCS subsidy in all sensitivity analyses, but the price reduction is generally small. Total power production in 2020-2050 increases by 0.3-0.9 per cent in the six scenarios. Supply of renewable power is also affected only slightly. Thus, we may conclude that subsidising CCS will have modest effects on market shares and total power production in the power market, even though it brings about a substantial acceleration of CCS deployment.

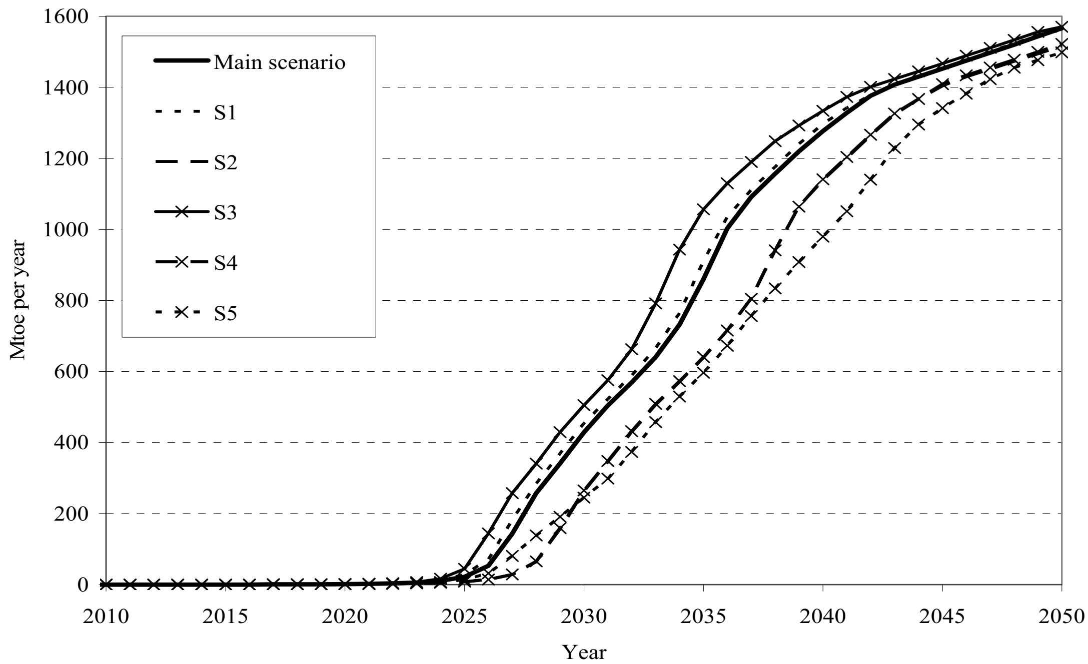

Fig. 11. Global power production with CCS in *Alternative scenario* II under different sensitivity analyses, Mtoe per year

[1] Obviously, *Alternative scenario* I also changes when we change parameter values. Thus, the Table displays changes between the new *Alternative scenarios* I and II.
[2] Note that S2 and S4 are almost overlapping in the Figure.

Conclusion

Major policy initiatives are required in order to reduce the growth and eventually the level of global CO_2 emissions. Both prices on CO_2 and subsidies to low-carbon energy or technologies such as CCS will probably be important elements of future climate policies around the world. This paper has examined the effects of such policies on international energy markets, with emphasis on the power market and prices of different energy goods. A detailed numerical model of international energy markets have been used to analyse these effects.

Our first conclusion is not very surprising. An ambitious climate policy will have substantial effects in the power market. Renewable power production will grow much faster over the next decades, and carbon capture will eventually become profitable. Conventional coal power production will be significantly reduced, whereas gas power will benefit. Prices of electricity will rise, coal prices will fall, whereas the effects on gas prices are mixed.

Our next conclusion is less obvious. Subsidising carbon capture on top of the climate policy will not impede the development of renewable power, even if CCS utilisation is substantially accelerated. We find that subsidising CCS will only slightly increase the total production of coal and gas power (with or without CCS), as emphasis is put on installing CCS equipment on the existing stock of coal and gas power plants. On the one hand, this increases the lifetime of especially coal power plants. On the other hand, as plants with carbon capture require more fuel input than conventional plants for the same amount of electricity produced, prices of coal and gas are driven upward, reducing the profitability of coal and gas power. Thus, electricity prices are only slightly reduced, and the effects on renewable power production are therefore small. Our sensitivity analyses confirm these overall findings.

Finally, the analysis suggests that both climate policy scenarios will eventually drastically reduce CO_2 emissions from the power sector – subsidising carbon capture will accomplish this much sooner. However, unless alternative energy sources or technologies are introduced in the other sectors of the economy, global emissions of CO_2 will continue to rise despite the ambitious climate policy examined in this analysis.

Acknowledgement

We are grateful for financial support from the Renergi Programme and the Petrosam Programme of the Research Council of Norway, and for valuable comments from Mads Greaker and Cathrine Hagem.

References

1. Archer, C.L., Jacobson, M.Z. (2005). Evaluation of global wind power, *Journal of Geophysical Research*, 110, D12110, doi:10.1029/2004JD005462.
2. Aune, F. R., Glomsrød, S., Lindholt, L., Rosendahl, K. E. (2005). Are high oil prices profitable for OPEC in the long run? Discussion Papers, No. 416, Statistics Norway.
3. Aune, F.R., Golombek, R., Kittelsen, S.A.C., Rosendahl, K.E. (2008). Liberalizing European Energy Markets, An Economic Analysis, Edward Elgar Publishing, Cheltenham.
4. Aune, F.R., Rosendahl, K.E., Sagen, E. (2009). Globalisation of natural gas markets – effects on prices and trade patterns, *The Energy Journal*, 30 (Special Issue: World Natural Gas Markets and Trade: a Multi-Modeling Perspective), 39-54.
5. Brooke A., Kendrick, D., Meeraus, A., Raman, R. (2005). GAMS, A User's Guide, GAMS Development Corporation, Washington DC.
6. Edmonds, J.A., Clarke, J., Dooley, J.J., Kim, S.H., Smith, S.J. (2002). Modelling greenhouse gas energy technology responses to climate change, Paper read at sixth international conference on greenhouse gas control technologies, September 30-October 4, at Kyoto, Japan.
7. EIA (Energy Information Administration) (2008). International Energy Outlook 2008, EIA, Washington, DC.
8. EU (2007). Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, Towards a European Strategic Energy Technology Plan, COM (2006) 847 final, EU, Brussels.
9. EU (2008)a. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. 2020 by 2020, Europe's climate change opportunity, COM (2008) 30 final, EU, Brussels.
10. EU (2008b). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Supporting Early Demonstration of Sustainable Power Generation from Fossil Fuels, COM (2008) 13 final, EU, Brussels.
11. Gerlagh R., van der Zwaan B.C.C. (2006). Options and Instruments for a deep cut in CO_2 emissions: carbon capture or renewables, taxes or subsidies? *The Energy Journal*, 27 (3), 25-48.
12. Golombek, R., Greaker, M., Kittelsen, S.A.C., Røgeberg, O., Aune, F.R. (2009). Carbon capture and storage technologies in the European power market, Discussion Papers, 603, Statistics Norway.
13. Greaker, M., Rosendahl, K.E. (2008). Environmental policy with upstream pollution abatement technology firms,

Journal of Environmental Economics and Management, 56, 246-259.
14. Grubb, M., Carraro, C., Schellnhuber, J. (2006). Technological change for atmospheric stabilization: introductory overview to the innovation modelling comparison project, *The Energy Journal* (Special Issue: Endogenous technological change and the economics of atmospheric stabilisation), 1-16.
15. Haq, Z. (2002). Biomass for Electricity Generation, July 2002 Energy Information Administration (EIA). http://www.eia.doe.gov/oiaf/analysispaper/biomass/index.html.
16. Hart R. (2008). The timing of taxes on CO_2 emissions when technological change is endogenous, *Journal of Environmental Economics and Management*, 55, 194-212.
17. IEA (2005). Projected costs of generating electricity, 2005 Update, IEA, Paris.
18. IEA (2006). Energy technology perspectives: scenarios & strategies to 2050, IEA, Paris.
19. IEA (2007a). World Energy Outlook 2007, IEA, Paris.
20. IEA (2007b). Capturing CO_2, Report by IEA Greenhouse Gas R&D Programme, IEA, Paris.
21. IEA (2010). Projected costs of generating electricity, 2010 Edition, IEA, Paris.
22. IPCC (2005). IPCC special report on carbon dioxide capture and storage, Cambridge University Press, Cambridge.
23. IPCC (2007). Climate Change 2007, The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Chapter 3), Cambridge University Press, Cambridge.
24. Johnson, T.L., Keith, D.W. (2004). Fossil electricity and CO_2 sequestration: how natural gas prices, initial conditions and retrofits determine the cost of controlling CO_2 emissions, *Energy Policy* 32, 367-382.
25. Kverndokk S., Rosendahl K.E. (2007). Climate policies and learning by doing: impacts and timing of technology subsidies, *Resource and Energy Economics*, 29, 58-82.
26. Martinsen, D., Linssen, J., Markewitz, P., Vogele, S. (2007). CCS: a future CO_2 mitigation option for Germany? – A bottom-up approach, *Energy Policy*, 35, 2110-2120.
27. McFarland, J., Reilly, J., Herzog, H. (2004). Representing energy technologies in top-down economic models using bottom-up information, *Energy Economics*, 26, 685-707.
28. MIT (2007). The Future of Coal, MIT, Cambrigde.
29. Newell, R.G., Jaffe, A.B., Stavins, R.N. (2006). The effects of economic and policy incentives on carbon mitigation technologies, *Energy Economics*, 28, 563-578.
30. Rao, S., Keppo, I., Riahi, K. (2006). Importance of Technological Change and Spillovers in Long-Term Climate Policy, *The Energy Journal*, Special Issue: Endogenous Technological Change and the Economics of Atmospheric Stabilisation, 123-139.
31. Requate, T., Unold, W. (2003). Environmental policy incentives to adopt advanced abatement technology: will the true ranking please stand up? *European Economic Review*, 47, 125-146.
32. Riahi, K., Rubin, E. S., Taylor, M. R., Schrattenholzer, L., Hounshell, D. (2004). Technological learning for carbon capture and sequestration technologies, *Energy Economics*, 26, 539-564.
33. Rosendahl, K.E., Sagen, E. (2009). The Global Natural Gas Market. Will transport cost reductions lead to lower prices? *The Energy Journal*, 30 (2), 17-40.
34. Rubin, E.S., Chen, C., Rao, A. B. (2007). Cost and performance of fossil fuel power plants with CO_2 capture and storage, *Energy Policy*, 35, 4444-4454.
35. *The Energy Journal*, 2006. Special Issue: Endogenous Technological Change and the Economics of Atmospheric Stabilisation.
36. de Vries, B.J.M., van Vuuren, D.P., Hoogwijk, M.M. (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.