Economic comparison of greenhouse gas mitigation options in Germany

Katja Schumacher
German Institute for Economic Research (DIW Berlin)
Germany
kschumacher@diw.de

Ron Sands
Joint Global Change Research Institute
USA
ronald.sands@pnl.gov

Keywords
climate change, greenhouse gas mitigation, general equilibrium modelling, energy efficiency, CO_2 capture and storage, fuel switch, Germany

Abstract
At least four classes of greenhouse gas mitigation options are available: energy efficiency, fuel switching, introduction of carbon dioxide capture and storage along with electric generating technologies, and reductions in emissions of non-CO_2 greenhouse gases. These options vary by cost, timing, and our ability to represent them in an economic analysis. Our objective is to provide a balanced analysis of these classes, across a variety of carbon policy scenarios, for Germany. Policy scenarios are represented as a response to varying levels of a carbon price, either applied economy-wide or targeted at energy-intensive sectors of the economy according to the EU emissions trading scheme. We use the Second Generation Model (SGM), an economy-wide computable general equilibrium model that embodies energy and other greenhouse gas mitigation possibilities. Energy efficiency options are represented in the standard Computer General Equilibrium (CGE) format, where non-energy inputs substitute for energy inputs within economic production functions, or system of consumer demand equations, as the price of energy increases relative to other goods. The electric power sector provides substantial opportunities for fuel switching and the deployment of advanced electricity generating technologies with and without CO_2 capture and storage. Our methodology relies on engineering descriptions of electricity generating technologies and how their competitive positions varies with a carbon price or change in fuel price. Furthermore, we allow for reduction of emissions of non-CO_2 gases, which adds a set of mitigation opportunities not usually included in energy-economic modeling efforts.

Introduction
At least four classes of greenhouse gas mitigation options are available: energy efficiency, fuel switching, introduction of carbon dioxide capture and storage (CCS) along with electric generating technologies, and reductions in emissions of greenhouse gases other than carbon dioxide (CO_2). These options vary by cost, timing, and our ability to represent them in an economic analysis. Our objective in this paper is to provide a balanced analysis of these classes, across a variety of carbon policy scenarios for Germany. Policy scenarios are represented as a response to varying levels of a price for CO_2, either applied economy-wide or targeted at energy-intensive sectors of the economy.

Our approach is to use a computable general equilibrium (CGE) economic model as a core model and integrating tool. Our model presents a flexible tool for simulating greenhouse gas emissions that can accommodate a wide variety of assumptions about electricity technologies, carbon prices, fuel prices, and baseline energy consumption. Our methodology relies on engineering descriptions of electricity generating technologies and how their competitive positions varies with a carbon price or change in fuel price. Moreover, it allows for reduction of emissions of non-CO_2 gases, which adds a set of mitigation opportunities not usually included in energy-economic modeling efforts.

Specifically, we use the Second Generation Model (SGM; Edmonds et al., 2004; Sands, 2004), an economy-wide computable general equilibrium model that embodies energy and other greenhouse gas mitigation possibilities. Energy efficiency options are represented in the standard CGE format, where non-energy inputs substitute for energy inputs within economic production functions, or system of consumer demand equations, as the price of energy increases relative to other goods. The electric power sector provides substantial opportunities for fuel switching and the deployment of advanced electricity generating technologies in both a projected baseline and in alternative carbon policy scenarios. Opportunities for reductions in emissions of the non-CO_2 gases; methane, nitrous oxide, and the F-gases; are handled differently. Here, we use exogenous projections and marginal abatement cost curves derived from an Energy Modeling Forum study.

We exercise our modeling framework for Germany under various hypothetical policy scenarios: (1) all sectors of the economy face a common carbon price; (2) carbon incentives are targeted to the electric power and energy-intensive industries (i.e. those covered by the EU emissions trading scheme); and (3) with and without consideration of non-CO_2 greenhouse gas mitigation options. Mitigation policies are represented with a set of constant-CO_2-price experiments covering a range of CO_2 prices high enough so that CCS technologies can at least break even.

Section 2 gives a brief overview of historical and current greenhouse gas emissions and reduction efforts in Germany. We introduce the SGM model in Section 3 and describe how it can be used to analyze the costs of greenhouse gas mitigation under different policy and technology assumptions. We simulate the potential role of coal integrated gasification combined cycle (IGCC), natural gas combined cycle (NGCC), carbon dioxide capture and storage (CCS), and wind power from the present through 2050. In Section 4, we discuss the economic and environmental results of the policy scenarios.

Background

Germany is one of the largest greenhouse gas emitters in the European Union, accounting for about one-fourth of European Union (EU) greenhouse gas emissions. In 2004, Germany emitted greenhouse gas emissions of about 1009 million t CO_2-equivalent (DIW, 2006). CO_2 emissions accounted for the major share (87.6 %) of overall greenhouse gas emissions in Germany, while non-CO_2 greenhouse gases amounted to 12.4 % of total greenhouse gas emissions. Compared to the base year[1], greenhouse gas emissions were 17.6 % lower in 2004. Within the burden sharing agreement under the Kyoto Protocol, Germany is committed to reduce greenhouse gas emissions (GHG) by 21 % in 2008-2012 compared to 1990. Assuming the recent downward trend will be continued, this target is likely to be met. A long-term national target is to reduce GHG emissions by 40 % by year 2020 relative to 1990.

A substantial portion of greenhouse gas emissions is produced by the electricity system. CO_2 emissions due to fossil fuel combustion for electricity production amount to more than 40 % of total CO_2 emissions in Germany. At the same time, Germany is facing a major renewal and restructuring process in electricity generation. Within the next two decades, up to 50 % of current electricity generation capacity may retire because of end-of-plant lifetime and the nuclear phase-out pact of 1998.

Nitrous oxide (N_2O) and methane (CH_4) account for the largest shares of non-CO_2 greenhouse gases followed by the F-gas, HFC. From 1990 to 2004, N_2O and CH_4 emissions have been declining (Figure 1). For CH_4, this was achieved by lowering levels of coal production, reducing sizes of livestock herds and carrying out waste-management measures such as reducing landfill storage of untreated household waste (via intensified recycling of biological waste and increased thermal treatment of unrecycled waste) and intensified collection and use of landfill gas. Modernization of gas-distribution networks and conversions from liquid to gas fuels, in smaller combustion systems, also contributed to emissions reductions (NC3, 2002).

For N_2O, the reduction is mainly due to technical measures introduced in the industrial sector to reduce adipic acid production. Those measures were part of the voluntary agreement of industries to reduce greenhouse gas emissions (NC3, 2002). The reductions were achieved even though emissions reductions in agriculture were counterbalanced by growth in emissions from road transports. HFCs grew by about 40 % over the last decade as a result of increase use of HFCs as a substitute for CFCs. PFC compounds, on the contrary, have been considerably reduced since 1990. The reduction has been brought about mainly through reduction of emissions in the aluminum industry (NC3 2002). SF_6 emissions have undergone substantial only slight changes in the last decade (NC3, 2002).

SGM-Germany

This section provides information on the model employed to conduct the economic analysis of greenhouse gas mitigation options in German. The analysis brings together historical data on the German economy and energy system, parameters of advanced generating technologies, policies governing nuclear and renewable energy, and population projections. We use a computable general equilibrium model, the Second Generation Model (SGM), as an integrating tool.

References for SGM include Edmonds et al. (1993), MacCracken et al. (1999), Edmonds et al. (2004), and Sands (2004). Three basic types of data are used to construct SGM-Germany. The first is the 1995 input-output table for Germany that provides an overall economic framework (Statistisches Bundesamt, 1995). The second is a 1995 energy balance table for Germany, which is essentially an energy input-output table (AGEB, 1999). These two tables are combined into a hybrid input-output table with units of joules for energy inputs, and units of 1995 DM for other inputs. Use of the hybrid input-output table ensures calibration to 1995 energy flows, and ensures that energy balance is maintained throughout all model time steps. The third basic data set is engineering costs for each electric generating technology. This is used to construct a fixed-coefficient production function for each generating technology.

SGM-Germany is constructed with the 18 production sectors shown in Figure 2. Production sectors are organized to be useful for questions related to climate policy with an emphasis on energy production, energy transformation, and energy-intensive industries. Most services are aggregated into a single production sector, the "everything else" sector.

1. The base year is 1990 for CO_2, CH_4 and N_2O emissions and 1995 for emissions of F-gases (HFC, PFC, SF_6).

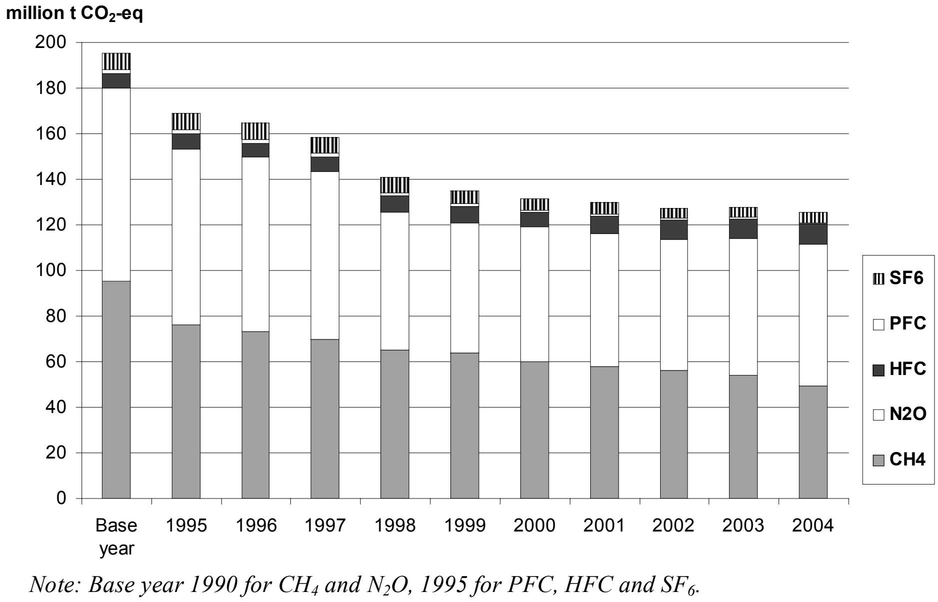


Figure 1 Non-CO_2 greenhouse gas emissions in Germany, 1995-2004.

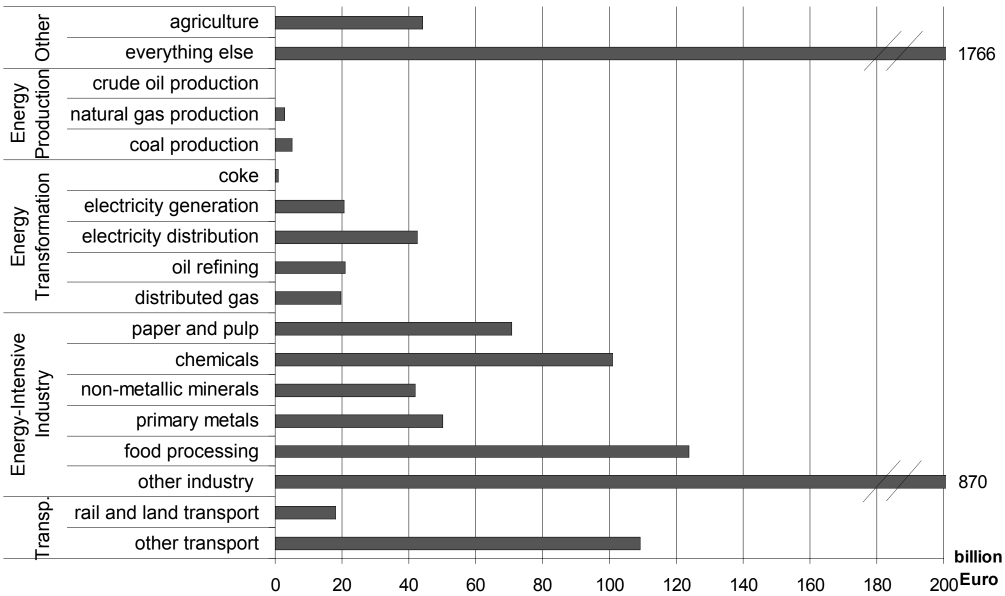
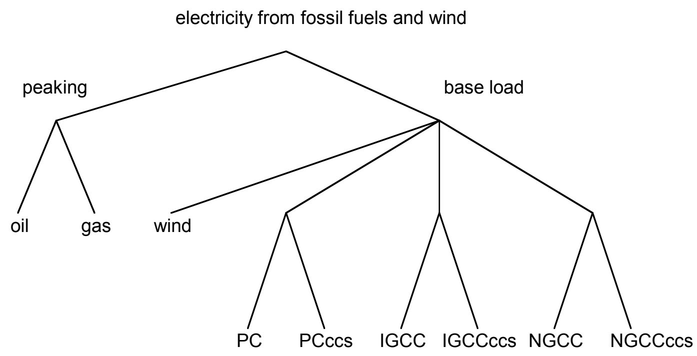


Figure 2 Production in SGM-Germany 1995 (billion EURO).

SGM-Germany operates in five-year time steps from 1995 through 2050 and each production activity has a capital stock segmented into five-year vintages. Capital lifetimes are typically 20 years in SGM, except for electricity generating technologies which are assigned lifetimes of 35 years. Old vintages of capital operate as a fixed-coefficient technology, while new vintages can be fixed-coefficient (in the energy transformation sectors) or constant-elasticity-of-substitution (CES). Therefore, new vintages of capital have a greater response to changes in relative prices, including carbon prices, than do old vintages of capital.

The cost of meeting any particular carbon emissions constraint depends on the set of technologies and the amount of time available for capital stocks to adjust to a new set of equilibrium energy and carbon prices. All production sectors outside of electricity generation operate with a single technology, but the electricity sector includes many individual technologies. Each electric generating technology is represented by an individual fixed-coefficient production function; a logit algorithm determines the share of electricity generated by each technology as a function of the levelized cost per kWh. McFarland et al. (2004) use a similar approach, except that a nested CES production function is used to distinguish electric generating technologies. See Sands (2004) for a more complete description of the logit allocation procedure.

Figure 3 provides the nested logit structure of electricity technologies employed in SGM-Germany. At each nest, technologies compete on levelized cost per kWh. If the cost per



Note: "NGCCccs" represents NGCC with CO_2 capture and storage, "IGCCccs" represents coal IGCC with CO_2 capture and storage, "PCccs" represents pulverized coal with CO_2 capture and storage.

Figure 3 Nested logit structure of electric generating technologies in SGM-Germany

kWh is equal among competing technologies in a nest, then each technology receives an equal share of new investment. A parameter at each nest determines the rate that investment shifts among technologies as levelized costs diverge. As a carbon price is introduced, the levelized cost per kWh increases for all generating technologies that emit CO_2. Technologies that are less carbon intensive receive a larger share of new investment than before the carbon price was introduced.

Technical change in the electricity sector occurs over time as a shift across generating technologies as new technologies become available and as relative prices, especially among fossil fuels, change. Engineering characteristics of any specific generating technology remain constant over the model time horizon. A parameter of the logit allocation algorithm governs the rate that investment across generating technologies may shift in response to changes in prices. This parameter is different for each nest in Figure 3.

Technical change in production sectors outside of electricity is a combination of price-induced movement along a production function isoquant, and exogenous change over time in technical coefficients of the production function. These changes in technical coefficients are analogous to autonomous energy efficiency improvement and autonomous labor efficiency improvement and are used primarily to construct a baseline scenario of energy consumption and economic growth. Substitution elasticities govern the rate that input-output ratios can change with respect to changes in prices.

This study includes no representation of electricity generation outside of Germany and therefore treats electricity trade on a scenario basis. The scenario used here fixes trade in electricity at base-year quantities for all model time steps.

Results

This study is designed to provide an economic comparison across a range of greenhouse gas mitigation scenarios for Germany. The scenarios vary across the available mitigation options and coverage of the economy. We start out by presenting results for the electricity sector. We use the general equilibrium framework to conduct a baseline analysis and alternative policy scenarios in order to yield information on the future electricity mix and the role of carbon dioxide capture and storage technologies within this mix. We then present emissions projections and results on abatement costs and economic growth with and without the inclusion of greenhouse gas mitigation options. Our policy analysis consists of four constant-price scenarios at 10, 20, 30 and 50 EURO per ton of CO_2 starting in 2005. For the latter two scenarios, the carbon price is introduced in 2005 at 20 EURO per ton of CO_2 and increased to 30 and 50 EURO respectively by 2010. In the first set of results the carbon prices are applied to all sectors of the economy. In the second set of results, referred to as partial coverage, carbon incentives are targeted to the electric power and energy-intensive industries (i.e. those covered by the EU emissions trading scheme). New fossil technologies are introduced to the model beginning in 2015, while technologies with CCS and advanced wind are introduced after 2015.

ELECTRICITY SECTOR RESULTS

We use a general equilibrium model, SGM-Germany, that allows the introduction of advanced electric generating technologies and the projection of the future electricity mix with these technologies in a base case and under different assumptions about the CO_2 price.

Figure 4 shows the share of electricity generation by technology for an SGM-Germany baseline through year 2050, with total generation rising gradually over time. The share of nuclear power is exogenously reduced to zero by 2030. Wind power subsidized by the renewable energy law rises steadily and accounts for a share of 12 % of total electricity generation by 2030 and stays at this level thereafter. Advanced wind power that competes apart from the renewable energy law accounts for a small share of electricity generation, but its cost per kWh is still high relative to other generating technologies. Shares of NGCC and IGCC grow rapidly to replace all nuclear power and much of pulverized coal. All generating plants are modeled with a lifetime of 35 years.

CO_2 capture and storage is introduced after 2015, but has no market share in the baseline; its share increases with the carbon price and as old generating capital is retired. SGM-Germany operates in five-year time steps and capital stock is grouped into five-year vintages. New capital has flexibility to adjust to a new set of energy and carbon prices but old capital does not. Therefore, the full impact of a carbon price is delayed until all

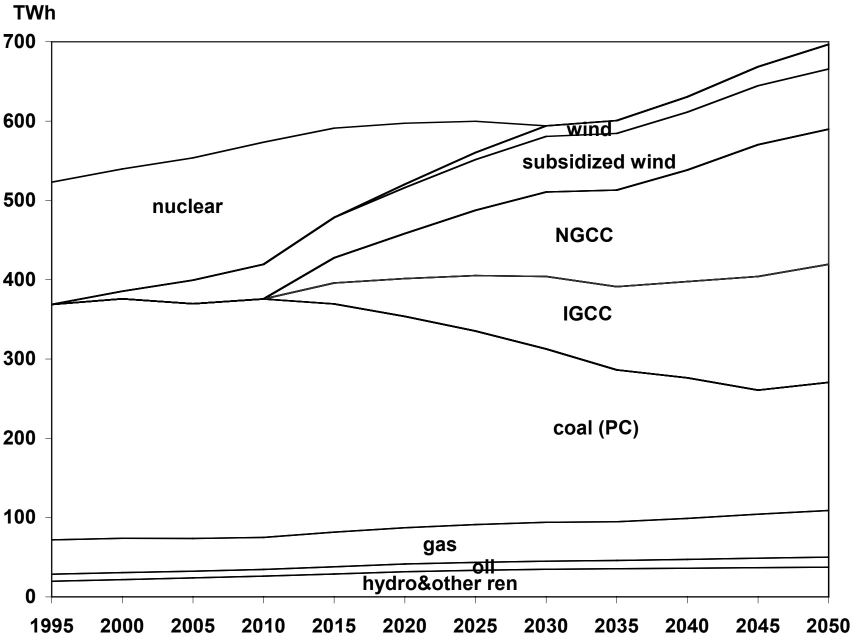


Figure 4 Baseline electricity generation in TWh

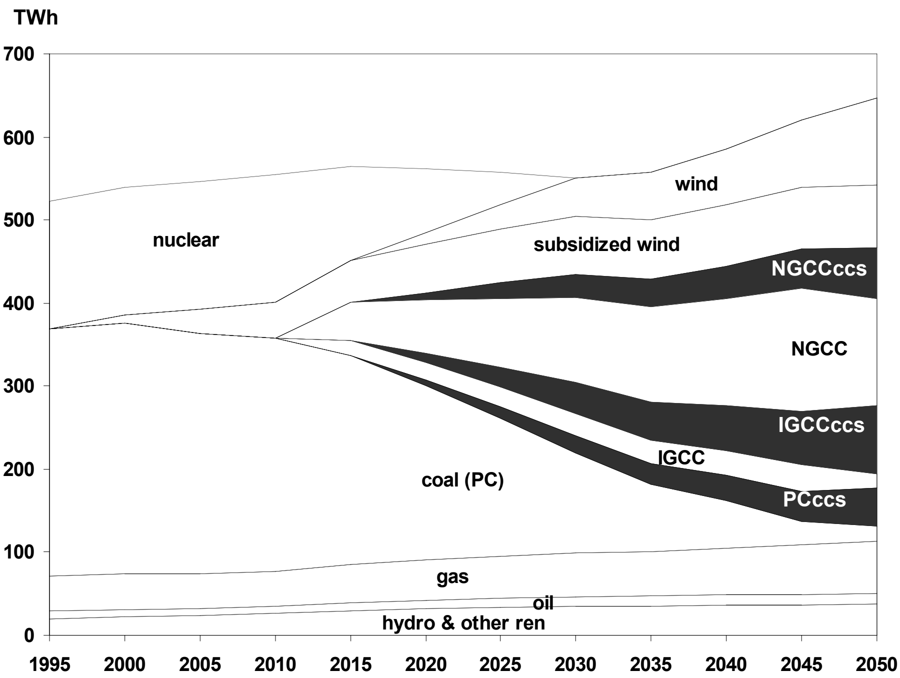


Figure 5 Electricity generation mix with carbon price 50 EURO per ton CO_2

old capital retires. Outside the electricity sector, SGM-Germany uses a capital lifetime of 20 years.

Figure 5 shows results with a CO_2 price of 50 EURO per t CO_2 introduced in year 2010 and held constant thereafter. Total electricity generation is slightly lower in the carbon price case than in the baseline. As electricity prices are already quite high in Germany, the additional costs induced by the carbon price does not have a very big impact, thus affecting electricity demand only slightly. The shares of wind and gas based production increase in the carbon price case, while the share of pulverized coal decreases. The carbon price is well beyond the breakeven price for CCS with IGCC, so a large share of IGCC capacity includes CCS by 2050. A carbon price of 50 EURO per t CO_2 is below the breakeven price for CCS with NGCC, so less than half of NGCC capacity includes CCS by 2050. CCS in this scenario applies to new generating plants only, and is phased in as old plants retire. With the carbon price, energy technologies that are less carbon-intensive increase their share of electricity generation. At lower levels of carbon prices (20 to 50 EURO per t CO_2), CO_2 capture and storage technologies as well as advanced wind still come into place, but with a reduced share of generation.

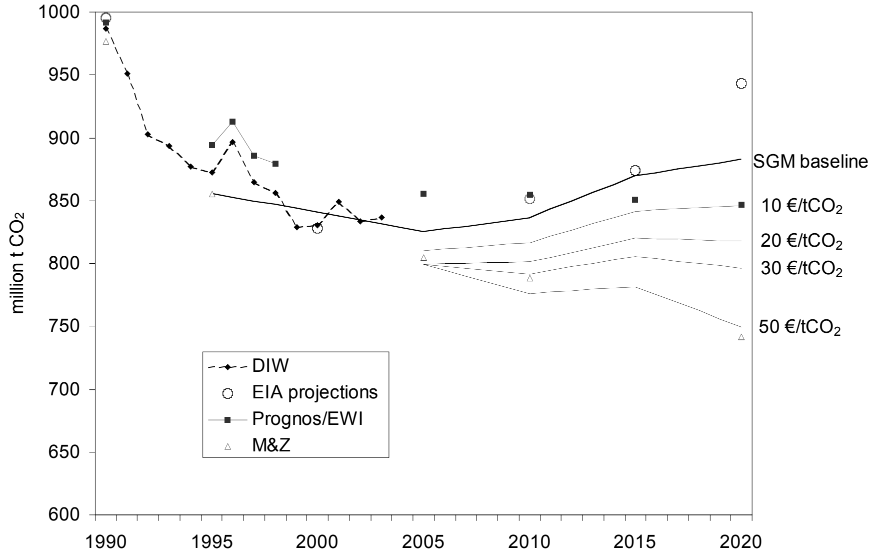


Figure 6 Projections of carbon dioxide emissions in Germany (Mt CO_2)

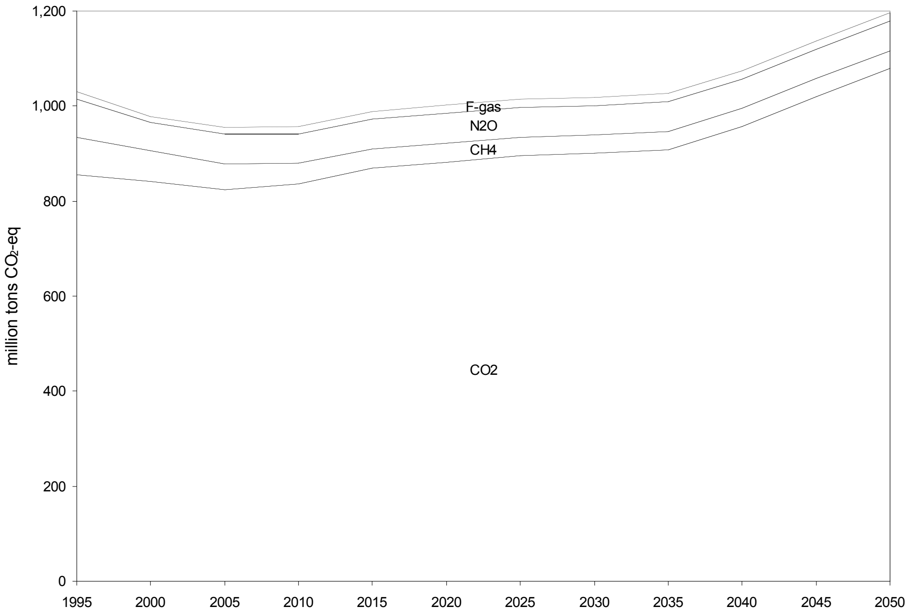


Figure 7 Greenhouse gas emissions pathway, baseline

CO_2 EMISSIONS RESULTS

Figure 6 provides a summary of several carbon emissions projections using the Second Generation Model (SGM) with the introduction of advanced electric generating technologies. Included in Figure 6 are baseline scenarios to the year 2020. Also included are projections of CO_2 emissions at CO_2 prices of 10, 20, 30 and 50 EURO per t CO_2. All of these scenarios are shown relative to historical CO_2 emissions (DIW 2006). The figure also includes projections of CO_2 emissions from Markewitz and Ziesing (M&Z 2004), Prognos/EWI (1999) and the U.S. Energy Information Administration (2004).

Baseline emissions rise slowly again after a steady decline until the year 2005. By 2020, however, emissions are only slightly above the base year 1995 level. A carbon price of 10 EURO per t CO_2 reduces emissions by 2.3 % compared to baseline emissions of 836 Mt CO_2 in 2010; a price of 20 EURO per t CO_2 reduces emissions by 4.2 % and a 50 EURO per t CO_2 price by 7.2 %.

RESULTS FOR ALL GREENHOUSE GASES

Baseline projections for CO_2 (from SGM) and the non-CO_2 greenhouse gases (from German data sources) are shown in Figure 7. Projections for the non- CO_2 gases are not available after 2030; therefore, baseline levels non-CO_2 gases are held constant after 2030. Emissions of CH_4 fall rapidly until 2010 and then gradually decline; N_2O emissions fall until year 2000 and then level off; emissions of the F-gases increase gradually until 2020 before becoming constant. Emissions of non-CO_2 GHGs are weighted at their 100-year global warming potential. All results are expressed as annual emissions in metric tons of CO_2-equivalent, through the year 2050.

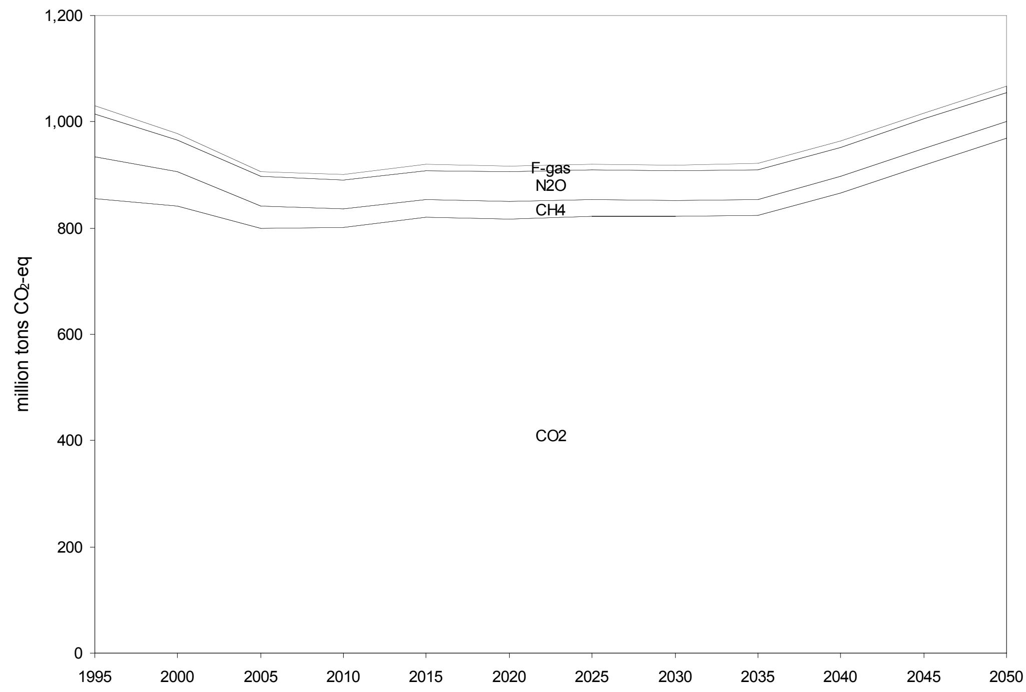


Figure 8 Greenhouse gas emissions pathway, 20 EURO per ton CO_2-eq

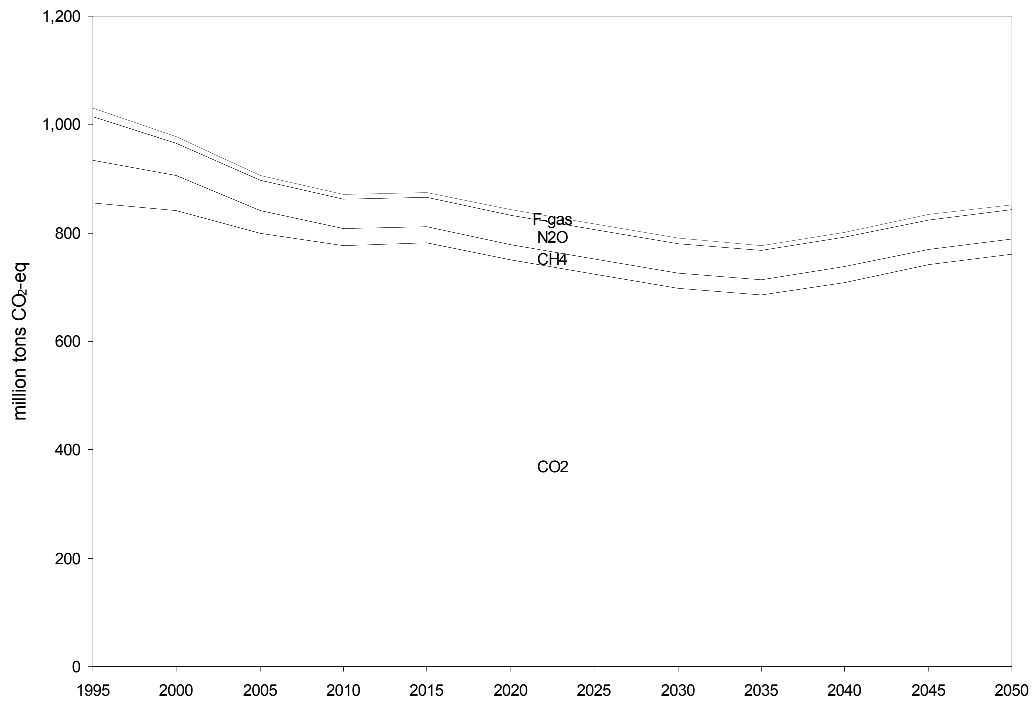


Figure 9 Greenhouse gas emissions pathway, 50 EURO per ton CO_2-eq

Figure 8 and Figure 9 show simulated greenhouse gas emissions at CO_2 prices of 20 EURO and 50 EURO respectively. Reductions in CO_2 emissions are derived from simulations using the Second Generation Model and include the option of carbon dioxide capture and storage from electricity generation. Reductions in emissions of the non-CO_2 greenhouse gases are represented by marginal abatement cost curves for a specific set of mitigation activities. We use cost curves constructed by the U.S. Environmental Protection Agency for the Stanford Energy Modeling Forum (EMF-21). EMF-21 cost curves and assumptions are documented in DeAngelo et al. (2006), Delhotal et al. (2006), and Ottinger et al. (2006). The EMF-21 cost curves were constructed for various world regions, including the United States and the EUROpean Union (EU-15). An application of the EMF-21 cost curves to greenhouse gas emissions in the United States is provided by Fawcett and Sands

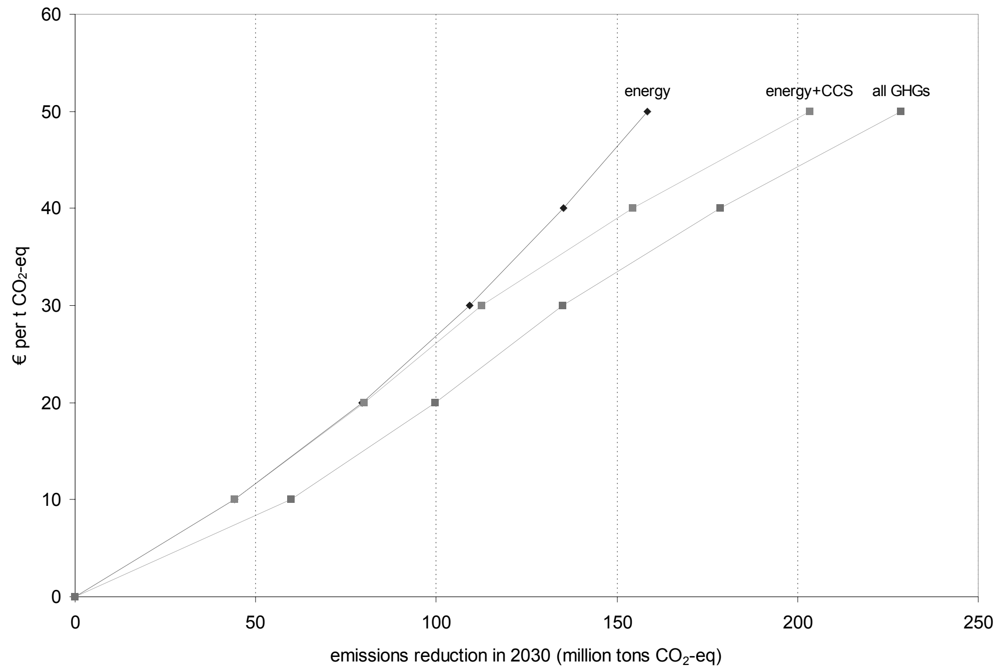


Figure 10 Simulated emissions reductions over a range of CO_2 prices, Germany 2030.

(2006). However, the cost curves are not differentiated by country within EU-15. We used the EU-15 cost curves, expressed as a percentage reduction from baseline at various CO_2 prices to represent emissions reduction opportunities in Germany. EMF-21 provided marginal abatement cost curves for the following activities involving methane and nitrous oxide: enteric fermentation (CH_4), coal mining (CH_4), natural gas production and distribution (CH_4), solid waste management (CH_4), agricultural soils (N_2O), and production of adipic and nitric acid (N_2O). In addition, marginal abatement cost curves were provided for three types of F-gases: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6).

Economic comparison

For any selected year, we can express emissions reduction potential in the form of marginal abatement cost curves. This is done in Figure 10 with separate components for energy system CO_2, carbon dioxide capture and storage, and the non-CO_2 greenhouse gases. This provides a graphical view of the relative sizes of reduction potential across major classes of greenhouse gas mitigation options, and how that varies across CO_2 prices.

Mitigation of energy-system CO_2 increases gradually along with the CO_2 price and has large potential at high CO_2 prices. Emissions reductions come from producer behavior, consumer behavior and fuel switching. Producers and consumers are able to substitute other goods for energy in consumption and production as the CO_2 price rises. Substitution elasticities in production and consumer demand elasticities are the key parameters that govern the price response. In addition, the mix of electricity generating technologies changes in response to a CO_2 price. As the CO_2 price increases, the relative cost per kWh of generating electricity changes across the generating technologies. Technologies that use carbon-intensive fuels, such as pulverized coal, receive a lower share of investment in new capital than before. Another elasticity parameter determines the rate that investment shares change in response to changes in the relative cost of generating electricity.

Carbon dioxide capture and storage is not available at low CO_2 prices, but can be a significant contributor to emissions reduction at CO_2 prices above 30 EURO per ton. For each electricity generating technology that can use CCS, one can calculate a break-even CO_2 price where the cost per kWh of generating electricity is the same with or without CCS. At this CO_2 price, we assume that half of any new investment in that generating technology uses CCS. We have not included a retrofit option for CCS; we assume that all CCS is installed on new generating plants. Therefore, the rate of CCS installation is limited by the rate that capital stock turns over in the electricity generating sector.

The non-CO_2 gases reach most of their full mitigation potential at low CO_2 prices. This is a consequence of using exogenous marginal abatement cost curves and simplifying assumptions on the requirements for new capital. The non-CO_2 mitigation options are considered to be primarily "end-of-pipe" processes that can be put in place by adding new equipment to existing capital, and need not wait for existing capital stocks to turn over.

PARTIAL COVERAGE OF ECONOMY

In the second set of results, referred to as partial coverage, carbon incentives are targeted to the electric power and energy-intensive industries (i.e. those covered by the EU emissions trading scheme). Specifically, the sectors covered by the CO_2 price are: coke production, electricity production, pulp and paper production, chemicals, non-metallic minerals, and primary metals production. We apply the same CO_2 price scenarios as above, i.e. a price of 10, 20, 30 and 50 EURO per ton of CO_2. For the latter two scenarios, the carbon price is introduced in 2005

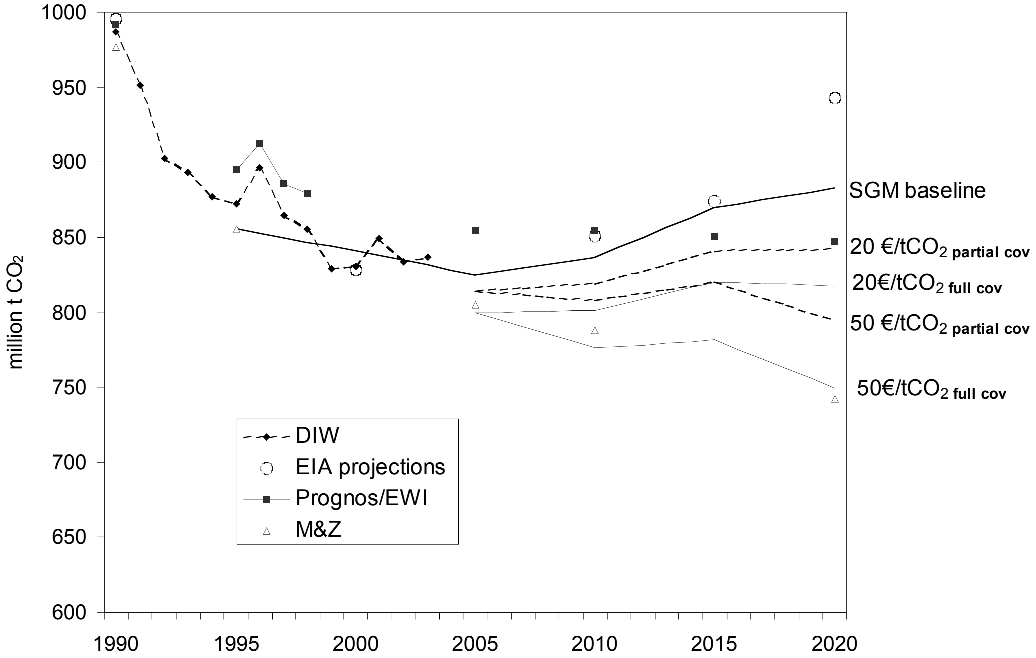


Figure 11 Projections of carbon dioxide emissions under baseline and policy scenarios: historical emissions, projections by EIA and M&Z, SGM baseline projection, SGM mitigation scenarios at 20 and 50 EURO per ton CO_2 with full coverage of the economy and with partial coverage.

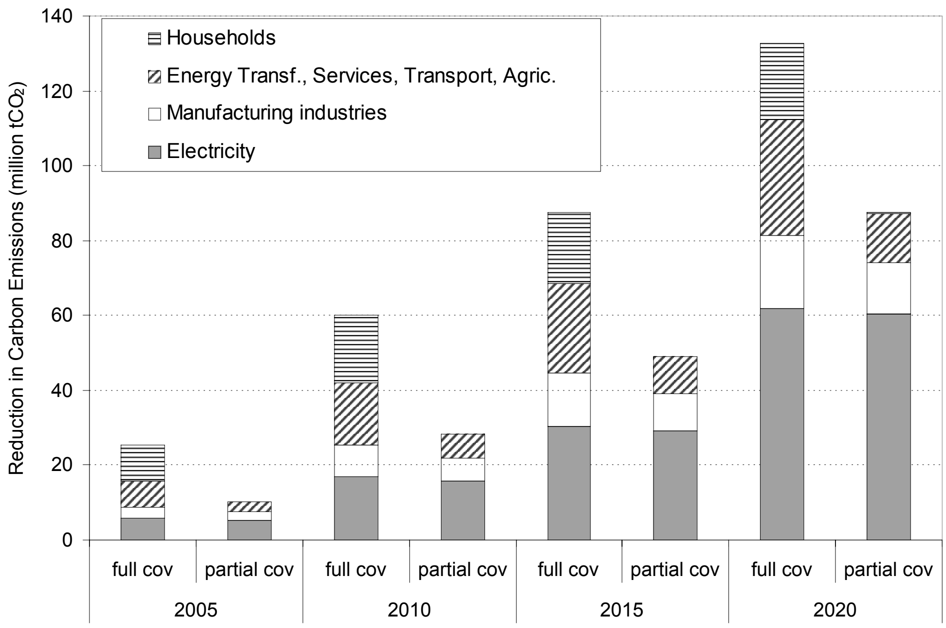


Figure 12 Decomposition of emissions reduction with a carbon price of 50 EURO per ton CO_2 fully and partially covering the economy

at 20 EURO per ton of CO_2 and increased to 30 and 50 EURO respectively by 2010.

As only specific sectors of the economy are tackled by the carbon price scheme, the resulting aggregate CO_2 emissions reductions are much lower than in the full coverage case (see Figure 11). By 2020, a carbon price applying to only parts of the economy brings down emissions by only about two thirds of what it would have been in the full coverage case.

The sectoral distribution of emissions reductions in the two cases in the 50 EURO per ton CO_2 scenario can be seen in Figure 12. At this price, the deviation from baseline increases over time as old capital is retired. The household sector is an exception, as it does not contain capital stocks in SGM. Therefore, the household sectors responds more quickly to a carbon price than other sectors. In the full coverage case, households contribute the largest share of emissions reductions in 2005. This changes over time and with higher carbon prices as new and

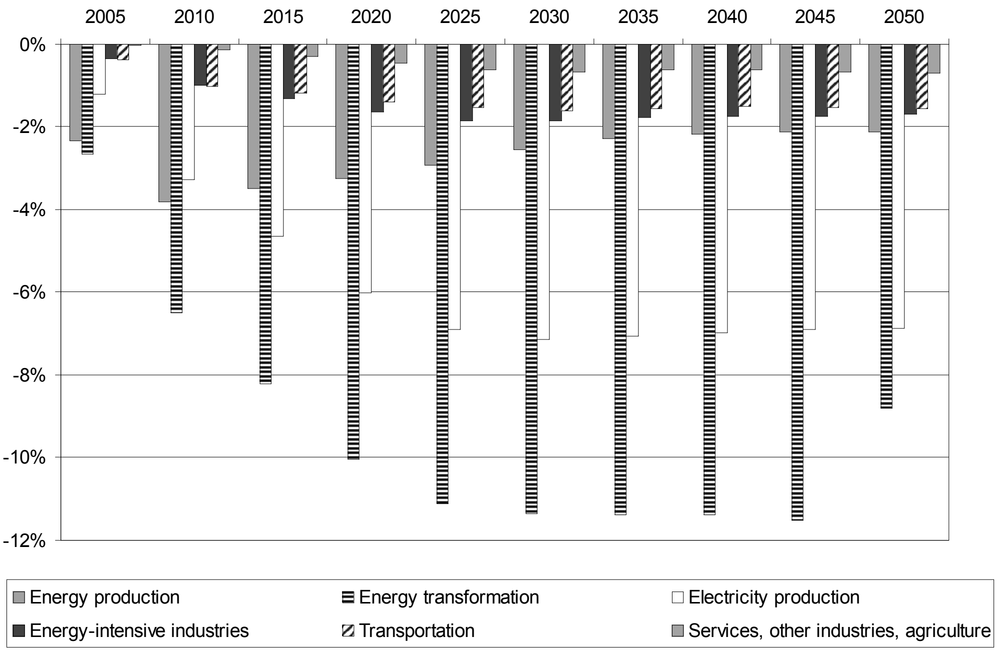


Figure 13 Change in sectoral output, 50 EURO per ton CO_2 applied to all sectors of the economy (full coverage), compared to baseline

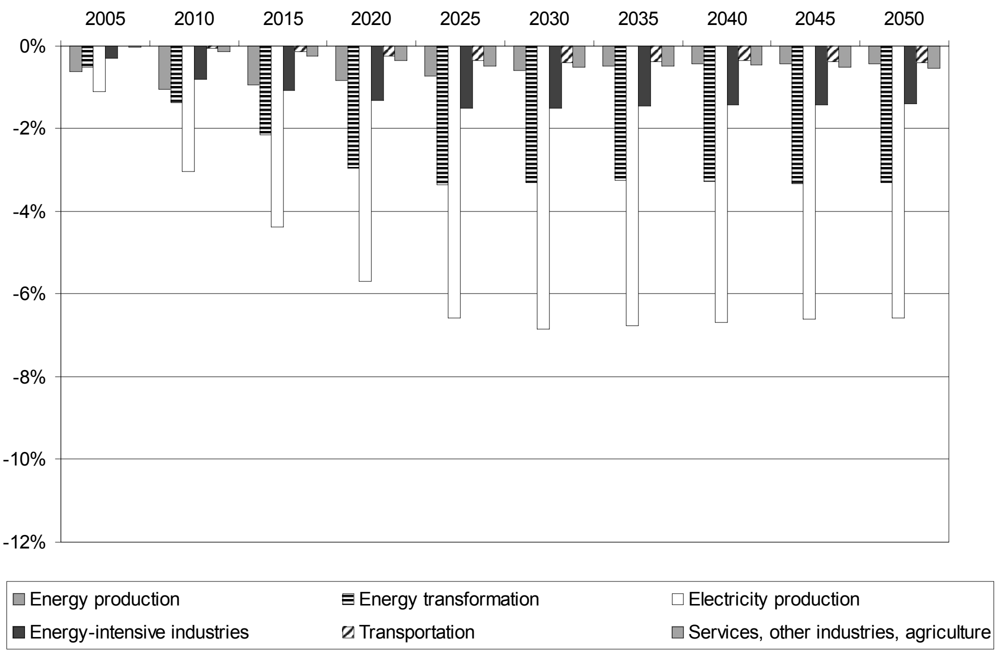


Figure 14 Change in sectoral output, 50 EURO per ton CO_2 applied to parts of the economy (partial coverage) compared to base case

advanced generating technologies come into place. By 2020, the electricity sector accounts for the largest share of emissions reductions (about 50 %) in the full coverage case.

The picture looks differently in the partial coverage case. In this case, the sectors covered by the carbon price scheme (electricity, energy intensive industries) account for about the same emissions reduction in the two cases. The sectors not covered by the carbon price scheme, however, do not contribute to emissions reductions. Manufacturing industries include energy-intensive and not energy-intensive industries. Thus, a difference in emissions reductions can be seen when a carbon price is only applied to the energy-intensive parts of manufacturing. Similarly, energy transformation sectors are covered by the scheme, while services, transport and agriculture do not face a carbon price and thus do not contribute directly to emissions reductions. The largest difference can be seen in the household sector, where no direct emissions reduction takes place in absence of a carbon price.

Figure 13 and Figure 14 show how quantity of gross output varies by sector aggregate in the 50 EURO per t CO_2 scenario relative to baseline. In forming sector aggregates, base year prices are used as weights. Most of the economy's output is contained in the services, other industries, and agriculture aggregate, which has a decrease in output of 0.67 % in the full coverage case and 0.53 % in the partial case where only parts of the economy are covered by the carbon price and lower overall emissions reduction is achieved. This turns out to be approximately the same as the percentage loss in real GDP. Other sectors are much smaller in terms of output, but are more sensitive to the carbon price. Electricity production has the largest and almost identical percentage reduction in output in both the full and partial coverage case. The reduction in output across energy-intensive industries is less than 2.0 % in both cases, yet it is slightly lower in the partial coverage case as only energy-intensive manufacturing sectors are covered by the carbon price scheme. The most pronounced difference between the full and the partial coverage case can be seen in the transportation and energy transformation (most oil refining) sector. Output losses for transportation sector are substantially lower in the partial coverage case, when not tackled by a carbon price. Consequently, a reduced loss in output from energy transformation can be observed as demand for petroleum products by the transport sector spurs production.

Gross Domestic Product (GDP) is measured in SGM as a Laspeyres quantity index with fixed base-year weights. GDP growth depends primarily on population growth and exogenous rates of technical change. The aggregate economy grows steadily in our baseline at 1-1.4 % (in terms of changes in real GDP) per year between 2000 and 2035. Annual growth then picks up in 2035 as the working-age population stabilizes and is no longer falling over time.

Conclusions

This study builds on previous analysis by Schumacher and Sands (2006), where the primary extensions here are the inclusion of non-CO_2 greenhouse gases and a broader set of carbon policies. The non-CO_2 greenhouse gas mitigation options are generally considered to be end-of-pipe options that can be deployed relatively quickly on both new and existing capital equipment. The rate that other greenhouse gas mitigation options can deploy is generally limited by the rate that existing capital stocks retire. The carbon policy scenarios in this study are designed to provide insights on the European Union emissions trading system, where carbon incentives are targeted at specific energy sectors.

One of the first things to notice about methane and nitrous oxide is that much of the mitigation potential, relative to the Kyoto reference year of 1990, is already in the baseline emissions scenario. This leaves a relatively small amount of additional reductions available for our policy scenarios. Even so, the contribution to potential greenhouse gas mitigation from the non-CO_2 greenhouse gases is still significant. One of the limitations of this study is that we did not have Germany-specific marginal abatement cost curves available. We used instead cost curves for the European Union constructed by the U.S. Environmental Protection Agency for the Stanford Energy Modeling Forum.

This study also included two types of carbon dioxide mitigation scenarios: one with the CO_2 price applied to all sectors of the economy, and another with the CO_2 price applied only to electricity generation and energy-intensive industries. The partial-coverage scenario is intended to better represent the emissions trading program in the European Union. One of the major differences between the full- and partial-coverage scenarios is that the transportation sector is no longer covered, and economic output from this sector does not fall as much in the partial-coverage scenario. Economic output, as well as carbon dioxide emissions, in the electricity sector and energy-intensive industries, changes very little between the two scenarios. In the partial-coverage case, about two thirds of carbon dioxide emission reductions come from the electricity sector.

This study is one step toward providing more realistic scenarios of greenhouse gas mitigation options in Germany. Future efforts could include the representation of specific technologies in the energy-intensive industries, as we have done with electricity generation technologies. Another possible extension is an analysis of the potential for biofuels, which become more cost-effective with higher oil prices and CO_2 prices.

References

Arbeitsgemeinschaft Energiebilanzen (AGEB). Energiebilanzen Deutschland (Energy Balances Germany), 1995. http://www.ag-energiebilanzen.de/. 1999.

DeAngelo, B., de la Chesnaye, F. C., Beach, R. H., Sommer, A., and Murray, B. C.: 2006, 'Methane and Nitrous Oxide Mitigation in Agriculture', *Energy Journal* (forthcoming).

Delhotal, K., de la Chesnaye, F. C., Gardiner, A., Bates, J., and Sankovski, A.: 2006, 'Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry', *Energy Journal* (forthcoming).

DIW Berlin (German Institute for Economic Research), 2006. Economic Bulletin 12, Wochenbericht Nr. 12, March 2006. www.diw.de.

Edmonds, J.A., Pitcher, H.M., Barns, D., Baron, R., Wise, M.A., 1993. Modeling Future Greenhouse Gas Emissions: The Second Generation Model Description, in: Klein, L.R., Lo, F. (Eds), Modelling Global Change. United Nations University Press, New York.

Edmonds, J.A., H.M. Pitcher, and R.D. Sands. 2004. Second Generation Model 2004: An Overview. Pacific Northwest National Laboratory.

Enquete, 2001. Prognos IER/WI, Szenarienerstellung Zwischenbericht: Basisdaten für die Szenarienerstellung, 21. Nov. 2001, Enquete Kommission 'Nachhaltige Energieversorgung' des Deutschen Bundestages.

Enquete, 2002. Endbericht „Nachhaltige Energieversorgung unter den Bedingungen der Globalisierung und der Liberalisierung". Enquete Kommission, Deutscher Bundestag, 14. Wahlperiode.

Fawcett, A.A., and Sands, R.D.: 2006, 'Non-CO_2 Greenhouse Gases in the Second Generation Model', *Energy Journal* (forthcoming).

MacCracken, C.N., Edmonds, J.A., Kim, S.H., Sands, R.D., 1999. The Economics of the Kyoto Protocol, in: Weyant, J., (Ed.), The Costs of the Kyoto Protocol: A Multi-Model Evaluation. The Energy Journal, special issue.

Markewitz, P., Ziesing, H.-J. (Eds.), 2004. Politikszenarien für den Umweltschutz: Langfristszenarien und Handlungsempfehlungen ab 2012. Eine Untersuchung im Auftrag des Umweltbundesamtes, Schriften des Forschungszentrums Jülich, Reihe Umwelt/Environment, Volume 50.

McFarland, J.R., Reilly, J.M., Herzog, H.J., 2004. Representing energy technologies in top-down economic models using bottom-up information. Energy Economics 26, 685-707.

NC3 2002. 3rd national communication to the UNFCCC: Third Report by the Government of the Federal Republic of Germany in accordance with the Framework Convention of the United Nations. Annex I. http://unfccc.int/national_reports/annex_i_natcom/submitted_natcom/items/1395.php

Ottinger, D., Godwin, D., and Harnisch, J.: 2006, 'Estimating Future Emissions and Potential Reductions of HFCs, PFCs and SF6', *Energy Journal* (forthcoming).

Prognos/EWI (Energiewirtschaftliches Institut der Universität Köln), 1999. Energiereport III. Die längerfristige Entwicklung der Energiemärkte im Zeichen von Wettbewerb und Umwelt. Stuttgart.

Sands, Ronald D. 2004. "Dynamics of Carbon Abatement in the Second Generation Model." *Energy Economics* 26 (4): 721-738.

Schumacher, Katja and R.D. Sands. 2006. "Innovative energy technologies and climate policy in Germany," *Energy Policy 34: 3929-3941*.

Statistisches Bundesamt, 1995. Volkswirtschaftliche Gesamtrechnung, Input-Output Tabellen 1995. Wiesbaden: Statistisches Bundesamt.

U.S. Energy Information Administration (EIA), 2004. International Energy Outlook. http://www.eia.doe.gov/oiaf/ieo/index.html, 2004.

Acknowledgements

This work was funded in part by the German Ministry of Education and Research (BMBF) within its socio-ecological research framework (SOEF). The views expressed by the authors do not necessarily reflect the views of the German Institute for Economic Research, the German government, Pacific Northwest Laboratory, or the U.S. Department of Energy.