Decomposition Analysis and Climate Policy in a General Equilibrium Model of Germany

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Abstract

Computable general equilibrium (CGE) models are used extensively in the analysis of alternative climate policies. A typical numerical simulation provides a scenario of energy consumption and greenhouse gas emissions from the present to 2050. This can be done for a reference scenario and alternative policy scenarios such as emissions trading or a carbon tax. The cost of meeting an emissions target depends on model features such as the ability to shift production across sectors, to shift production inputs away from energy, and the ability to shift across energy technologies.

In particular, the role of energy technologies is considered crucial in climate change mitigation, and the realism of climate policy simulations is improved by including engineering descriptions of key energy-intensive processes. In our analysis, we allow for an unconventional inclusion of energy technologies for electricity generation and steel production to capture the

interdependency of these processes as well as the interaction with economic activity in other sectors.

By looking at model output on energy consumption or emissions, it is not immediately clear to what extent these shift components contribute to a change in emissions, either over time for a single scenario or across scenarios at a point in time. Our objective is to partition an overall change in greenhouse gas emissions into explanatory components: energy efficiency, fuel switching, technology shift, shifts in sector output, carbon dioxide capture and storage, and loss in economic output due to deadweight loss.

We select the log-mean Divisia Index (LMDI) as a decomposition methodology to assess the relative contributions of these components. This methodology allows for a total change in emissions to be split into components that sum exactly to the total. We can construct emissions decompositions by production sector or economy-wide. We use energy and emissions scenarios based on model analysis with SGM-Germany, a computable general equilibrium model, applied to Germany. We construct a reference emissions scenario for Germany through 2050, along with several constant-CO2-price scenarios with CO2 prices up to 50 euros per ton of CO2.

For any given future year in the scenarios, we can construct emissions decompositions at various CO2 prices. We provide decompositions for year 2040 for the electricity sector and all sectors combined. An interesting result is that the decomposition provides a graphical representation of the contribution of carbon dioxide capture and storage (CCS) net of the CCS energy penalty. We also provide emissions decompositions over time for a policy scenario.

The results show the relative importance of the components in mitigating greenhouse gas emissions in Germany. They demonstrate that advanced energy technologies, such as advanced natural-gas-based steel production or CCS in electricity generation, and the interaction of these technologies, play a crucial role. This demonstrates that the inclusion of specific energy technologies in a CGE model helps isolate explanatory components that would be overseen in more aggregate analysis.

Keywords: greenhouse gas mitigation options; energy efficiency; fuel switch; carbon dioxide capture and storage; non-CO_2 greenhouse gases; general equilibrium modeling; economic effects; climate policy

JEL Classifications: Q43, C68, Q58, Q54

1. Introduction

At least four classes of greenhouse gas mitigation options are available: energy efficiency, fuel switching, introduction of carbon dioxide capture and storage (CCS) to electricity generation, 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 climate policy scenarios for Germany. Policy scenarios are represented as a response to varying levels of a price for greenhouse gas emissions, either applied economy-wide or targeted at energy-intensive sectors of the economy.

Our approach is to combine results from a computable general equilibrium (CGE) model for Germany and related analysis of non-CO_2 greenhouse gases. The CGE framework presents a flexible tool for simulating greenhouse gas emissions that can accommodate a wide variety of assumptions about electricity technologies, CO_2 prices, fuel prices, and baseline energy consumption. We use the CGE model to provide analysis of the energy efficiency, fuel switching, and CCS mitigation options. Analysis of the non-CO_2 greenhouse gas mitigation options is achieved using marginal abatement cost curves, expressed as a percentage reduction from baseline emissions, made available to the Stanford Energy Modeling Forum. Consistency between the two types of analysis is achieved by applying the same policy scenarios to each set of mitigation options. Allowing for a reduction of emissions of non-CO_2 gases adds a set of mitigation opportunities to the analysis that is not usually included in energy-economic modeling efforts.

We use the Second Generation Model (SGM; Edmonds et al., 2004; Sands, 2004), an economy-wide computable general equilibrium model, applied to Germany. 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 climate policy scenarios. Our methodology relies on engineering descriptions of electricity-generating technologies and how their competitive position varies with a CO_2 price or change in fuel price.

There are two parts to our analysis of non-CO_2 greenhouse gases for Germany: first we construct a baseline emissions scenario through 2050, and then simulate the impact of a price for greenhouse gas emissions using marginal abatement cost curves targeted to specific activities that emit methane, nitrous oxide, or one of the fluorinated greenhouse gases (F-gases). The baseline includes low-cost reductions in greenhouse gas emissions that are expected even without a CO_2-equivalent price. The marginal abatement cost curves determine a percentage reduction in greenhouse gas emissions, relative to the baseline, for any given CO_2-equivalent price.

We exercise our modeling framework for Germany under various hypothetical policy scenarios: (1) greenhouse gas incentives are targeted to the electric power and energy-intensive industries (i.e. those covered by the EU emissions trading scheme); (2) all sectors of the economy face a common price for greenhouse gas emissions; 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-equivalent prices high enough so that CCS technologies can at least break even.

Section 2 provides 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 advanced electricity-generation technologies including the option of carbon dioxide capture and storage (CCS). In Section 4, we discuss the environmental and economic results of the policy scenarios with a special focus on the potential contribution of each class of mitigation options. Section 5 summarizes the results and provides some conclusions.

2. Background

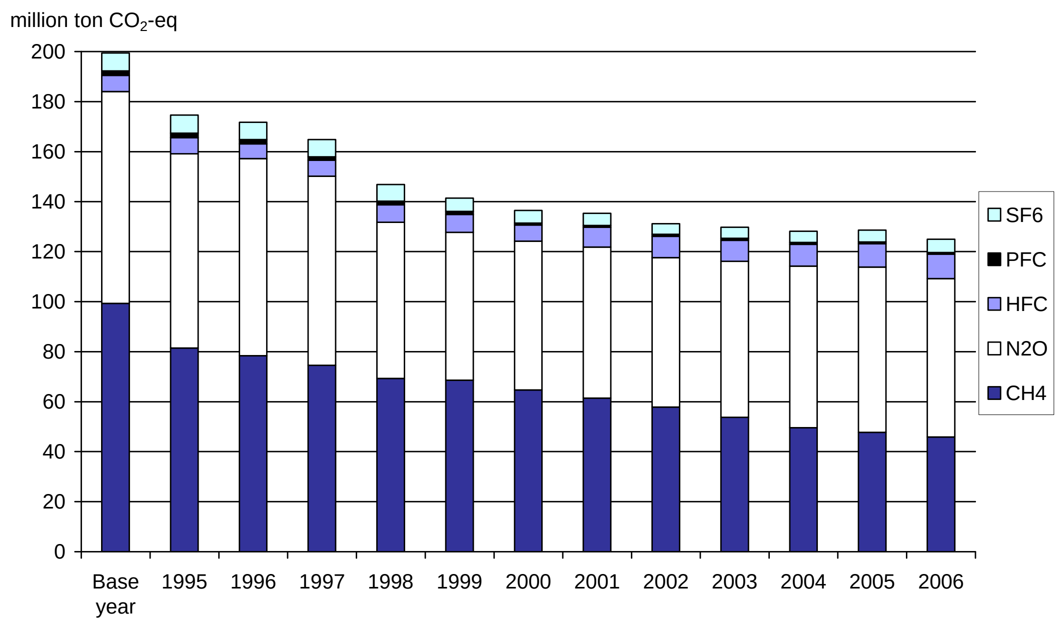
Germany is one of the largest greenhouse gas emitters in the European Union, accounting for about one-fourth of European Union (EU) greenhouse gas emissions. In 2006, Germany emitted greenhouse gases of about 1005 million t CO_2-equivalent (Ziesing, 2007 and 2008). CO_2 emissions accounted for the major 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 18,4% lower in 2006. 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 may be met. A medium-term national target is to reduce GHG emissions by 40% by year 2020 relative to 1990. This target is supported by an integrated Energy and Climate Program which was adopted by the German cabinet in August 2007 (BMU 2007).

Greenhouse gas emissions originate from many different sources. While CO_2 emissions can be linked to the combustion of fossil fuels and, to a lesser extent, fossil fuel use related industrial process emissions, non-CO_2 emissions emanate from activities that are not necessarily related to fossil fuel use. CH_4 emissions, for example, originate from non-energy activities such as cattle raising, rice fields, sanitary landfills, manure, and wastewater as well as energy related activities, such as production and distribution of natural gas, coal mining, combustion of biomass etc. Similarly, N_2O emanates from fertilizer use, transport-related combustion processes, and industrial processes. SF_6 stems from electrical switchgear and other industrial processes, and emissions of other F-gases result from purely industrial processing with no link to fossil fuel use.

In Germany, nitrous oxide (N_2O) and methane (CH_4) account for the largest shares of non-CO_2 greenhouse gases, followed by HFCs. From 1990 to 2005, 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 un-recycled waste) and intensified collection and use of landfill

[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).

gas. Modernization of gas-distribution networks and conversions from liquid to gas fuels, in smaller combustion systems, also contributed to emissions reductions (NC3, 2002).



Note: Base year 1990 for CH_4 and N_2O, 1995 for PFC, HFC and SF_6. Source: Ziesing (2007 and 2008).

Figure 1 Non-CO_2 greenhouse gas emissions in Germany, 1995-2006

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 in N_2O emissions were achieved even though emissions reductions from fertilizer use in agriculture were counterbalanced by growth in emissions from road transport. As to the F-gases, HFCs grew by about 40% over the last decade as a result of increased 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 only slight changes in the last decade (NC3, 2002).

3. Methods

This section provides information on the model employed to conduct the economic analysis of greenhouse gas mitigation options in Germany. 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. Section 3.2 introduces the methodology used to account for mitigation options for non-CO_2 greenhouse gas emissions.

3.1. SGM-Germany

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.

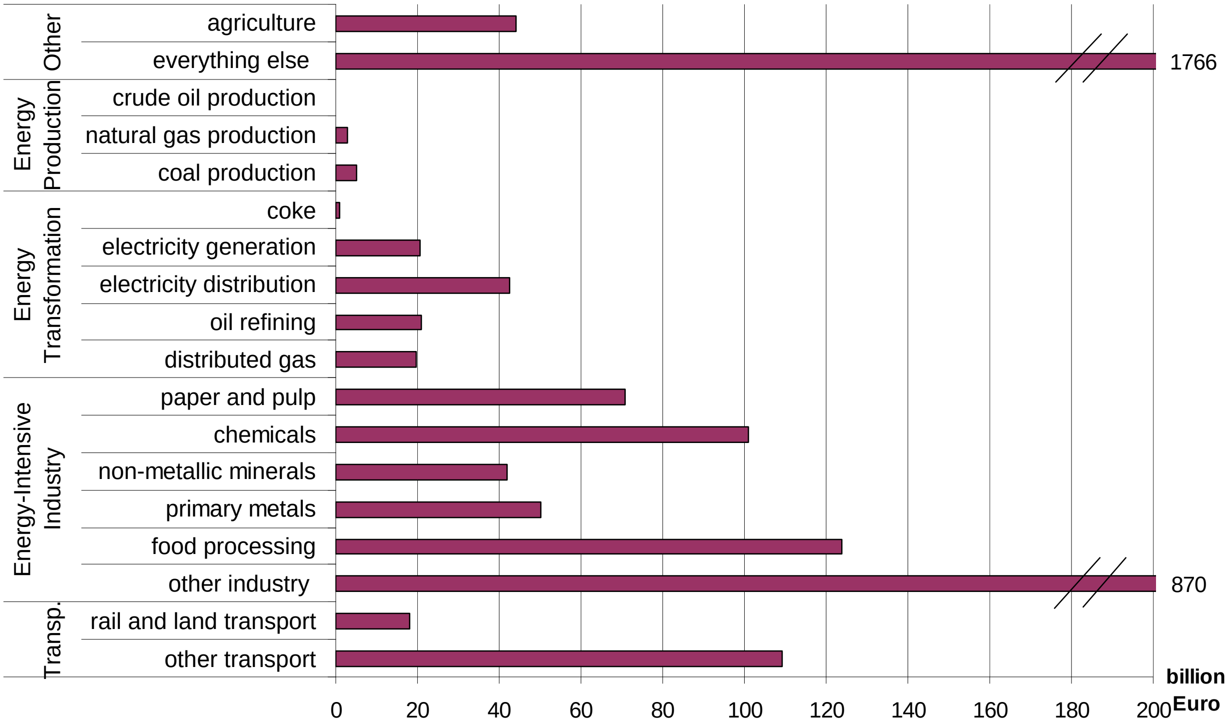


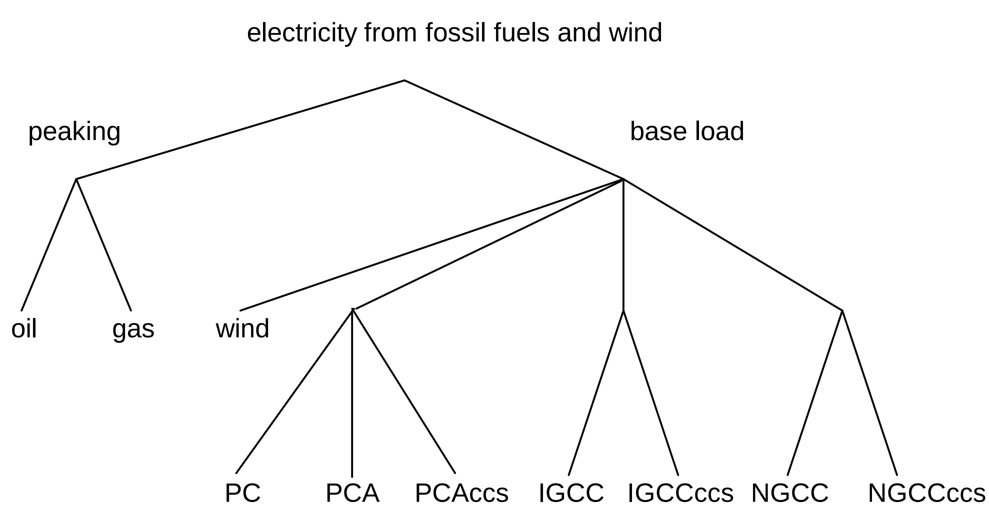
Figure 2 Production in SGM-Germany 1995 (billion Euro).

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 electricity-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 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.



Note: PC refers to conventional and PCA to advanced coal based electricity generation. "NGCCccs" represents NGCC with CO_2 capture and storage, "IGCCccs" represents coal IGCC with CO_2 capture and storage, "PCAccs" represents advanced pulverized coal with CO_2 capture and storage.

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

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.

3.2. Greenhouse gas emissions

Emissions of CO_2, are considered proportional in a fixed ratio to the energy content of the fuel used. This implies that they are linked to fossil fuel consumption in each economic sector and are calculated on a sector basis for each model time step. The introduction of a climate policy affects the cost of production and also the pattern of investment. This implies a change in the relative demand of factor inputs, in particular energy, and thus mitigation of CO_2 emissions.

Non-CO_2 emissions, however, are not limited to fuel use activities. Therefore, emissions of those gases require a different tracking procedure. Table 3.1 shows the greenhouse gases and their sources that are included in our analysis.

Table 3.1 Greenhouse gas emission sources

Gas	Source #	Emissions Source
CO_2	1	Oil combustion
	2	Gas combustion
	3	Coal combustion
CH_4	4	Coal production
	5	Enteric fermentation
	6	Natural gas and oil systems
	7	Solid waste
N_2O	8	Agricultural soil
	9	Industrial processes
	10	Manure
	11	Fossil fuels
	12	Waste
	13	Solvent use and other product use
HFCs	14	Ozone depleting substances substitutes
PFCs	15	Aluminum
	16	Semiconductor
SF_6	17	Electricity distribution
	18	Magnesium

We use SGM-Germany to simulate the development of energy consumption and CO_2 emissions from 1995 up to 2050, for both baseline and mitigation scenarios. Reductions in CO_2 emissions are obtained by operating SGM-Germany at various CO_2 price paths. Several advanced electricity generation options are available, including carbon dioxide capture and storage.

We construct a baseline scenario of non-CO_2 greenhouse gas emissions using exogenous information and projections of DIW (2006), Ziesing (2007 and 2008), Diekmann et al. (2005), UBA (2005), NC3 (2002), and Prognos/EWI (1999). In the mitigation scenarios, reductions in emissions of 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). Fawcett and Sands (2006) provide an application of the EMF-21 cost curves to greenhouse gas emissions in the United States. 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. No detailed information on marginal abatement costs for greenhouse gas emissions in Germany was available. However, since the structure of non-CO_2 greenhouse gas emissions in Germany and the EU-15 show a similar pattern (see Figure 4 for years 2000 and 2005), we have some confidence that the range of mitigation options for Germany is represented in the set of EU-15 options.

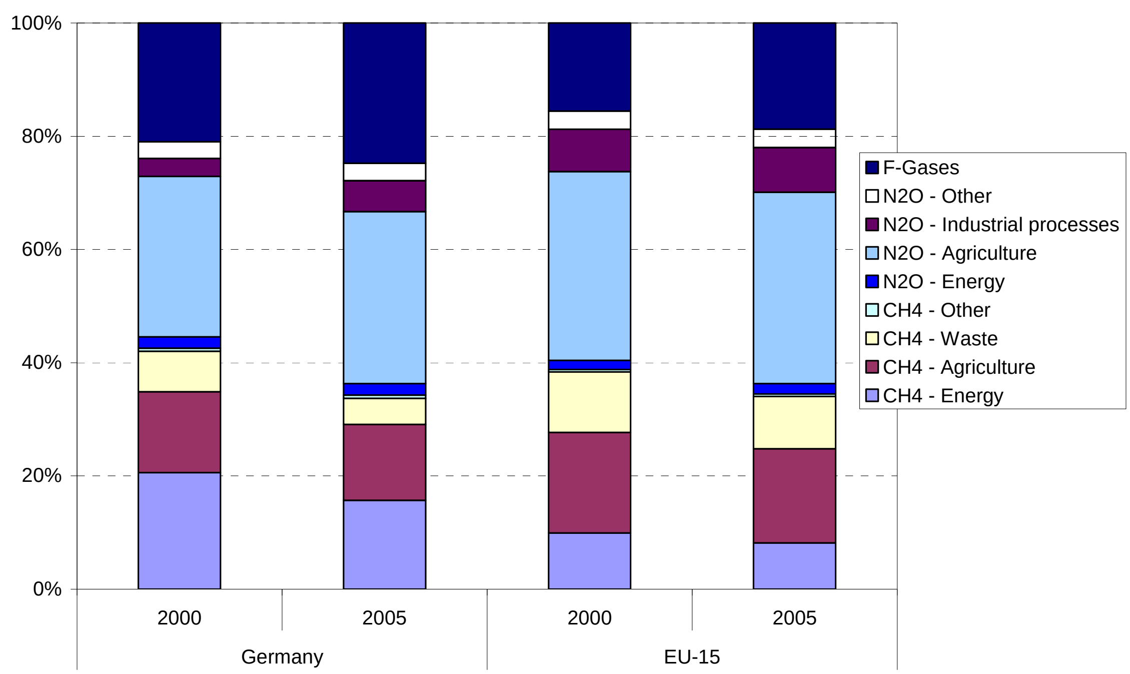


Figure 4 Structure of non-CO2-GHG emissions in Germany and EU-15 (2000 and 2005)

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).

4. 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 a CO_2 policy scenario that includes a stepwise CO_2 price increase from 10 € per ton of CO_2-eq in 2005, to 20 € per ton of CO_2 in 2010 and continues to increase to 50 € per ton of CO_2-eq in 2025; we also conduct five constant-price scenarios at 10, 20, 30, 40 and 50 € per ton of CO_2-eq starting in 2005. For the latter four scenarios, the CO_2-equivalent price is introduced in 2005 at 10 € per ton of CO_2-eq and increased to 20, 30, 40 and 50 € respectively by 2010 (compare Table 4.1). In the first set of results, referred to as partial coverage, CO_2 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. In the second set of results, the CO_2 prices are applied to all sectors of the economy. New fossil technologies are introduced to the model beginning in 2015, while technologies with CCS and advanced wind are introduced after 2015.

Table 4.1 Greenhouse gas price scenarios. All scenarios reach a maximum CO_2-equivalent price in 2025 and the price remains constant thereafter. These prices can be applied to either the entire economy (full coverage) or sectors covered by the EU emissions trading program (partial coverage).

CO_2 price scenario	**2000**	**2005**	**2010**	**2015**	**2020**	**2025+**
stepwise CO_2-eq price	0	10	20	30	40	50
10 € per t CO_2-eq	0	10	10	10	10	10
20 € per t CO_2-eq	0	10	20	20	20	20
30 € per t CO_2-eq	0	10	30	30	30	30
40 € per t CO_2-eq	0	10	40	40	40	40
50 € per t CO_2-eq	0	10	50	50	50	50

4.1. Electricity sector results

In this section, we draw on our detailed representation of advanced electric generating technologies in the general equilibrium model, SGM-Germany, and simulate the future electricity mix with these technologies including the option of CO_2 capture and storage technologies in a base case and under different assumptions about a CO_2 price.

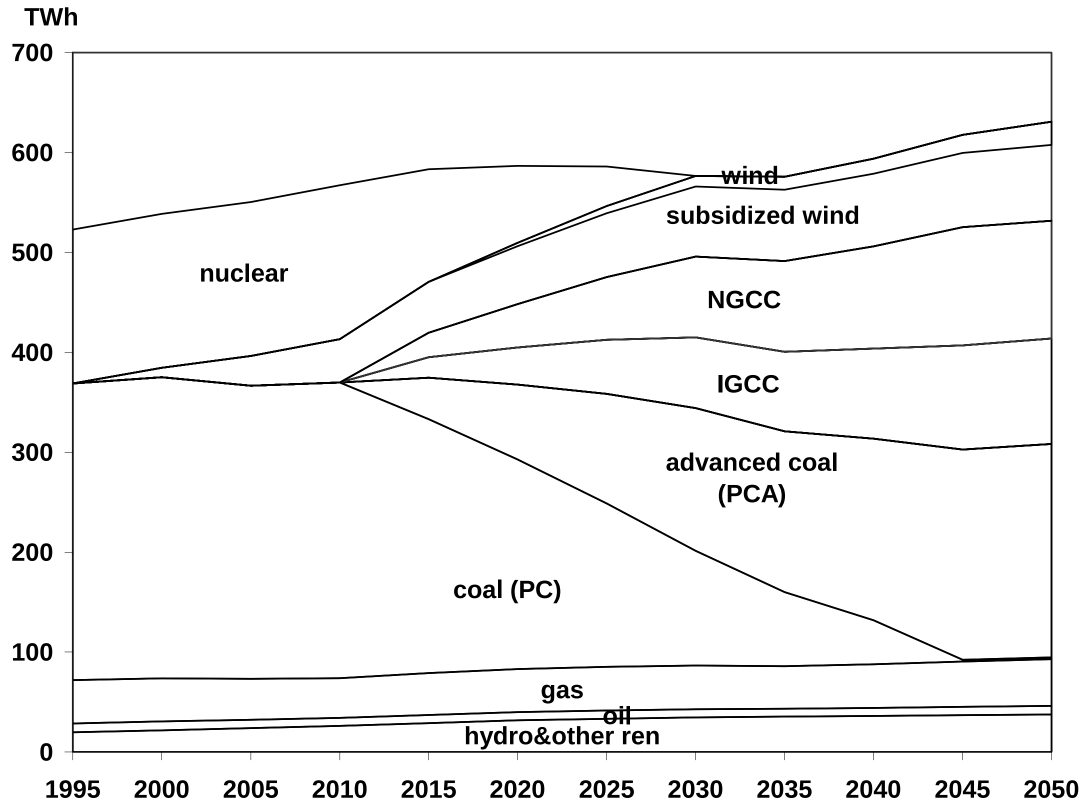


Figure 5 Baseline electricity generation in TWh

Figure 5 shows the baseline electricity generation mix by technology in SGM-Germany up to the year 2050. Total generation rises gradually over time. The share of nuclear power is exogenously reduced to zero by 2030, reflecting the German nuclear phase out[2]. 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. New electricity-generating technologies are introduced to the model beginning in 2015. Advanced wind power that is

[2] The gradual phasing-out of nuclear in Germany has been agreed upon in 2000 and is part of the nuclear law (2002). It prohibits new nuclear power plants to be built and restricts the lifetime of existing nuclear power plants to an average of 32 years and production from these plants to a maximum of 2.63 TWh of nuclear electricity. The agreement precisely tells how much electricity a power plant is allowed to produce before being closed down. Some amount of electricity generation may be transferred from older to newer plants.

assumed to not benefit from the renewable energy law and is assumed to compete in the market accounts for a small share of electricity generation, but its cost per kWh is still high relative to other generating technologies. The shares of advanced fossil fuel based technologies, i.e. NGCC, IGCC and advanced pulverized coal (PCA), grow rapidly to replace all nuclear power and much of conventional coal based power generation. All generating plants are modeled with a lifetime of 35 years.

CO_2 capture and storage (CCS) for fossil fuel based technologies is introduced after 2015. CCS does not gain a market share in the baseline; its share increases with the CO_2 price and as old generating capital is retired. SGM-Germany operates a capital vintage approach where capital stock is grouped into five-year vintages. New capital has flexibility to adjust to a new set of energy and CO_2 prices but old capital does not. Therefore, the full impact of a CO_2 price is delayed until all old capital retires.

The climate policy scenario consists of a stepwise CO_2 price increase (compare Table 4.1). As shown in Figure 6, total electricity generation is lower in the climate policy scenario than in the baseline. The impact of CO_2 price on electricity demand is relatively small, because electricity prices are already high in Germany so that the additional costs effect is small. The shares of advanced wind and natural gas based production increase in the climate policy case, while the shares of both conventional and advanced pulverized coal decrease. By 2050, the CO_2 price has increased to 50 € per ton and is well beyond the breakeven price for CCS with IGCC, so a large share of IGCC capacity includes CCS by then. The CO_2 price, however, remains below the breakeven price for CCS with PCA and also NGCC over the entire time horizon so substantially less PCA and 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 higher CO_2 prices, energy technologies that are less carbon-intensive (renewable technologies, CO_2 capture and storage for fossil fuel based technologies) increase their share of electricity generation. At lower levels of CO_2 prices (20 to 50 € 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.

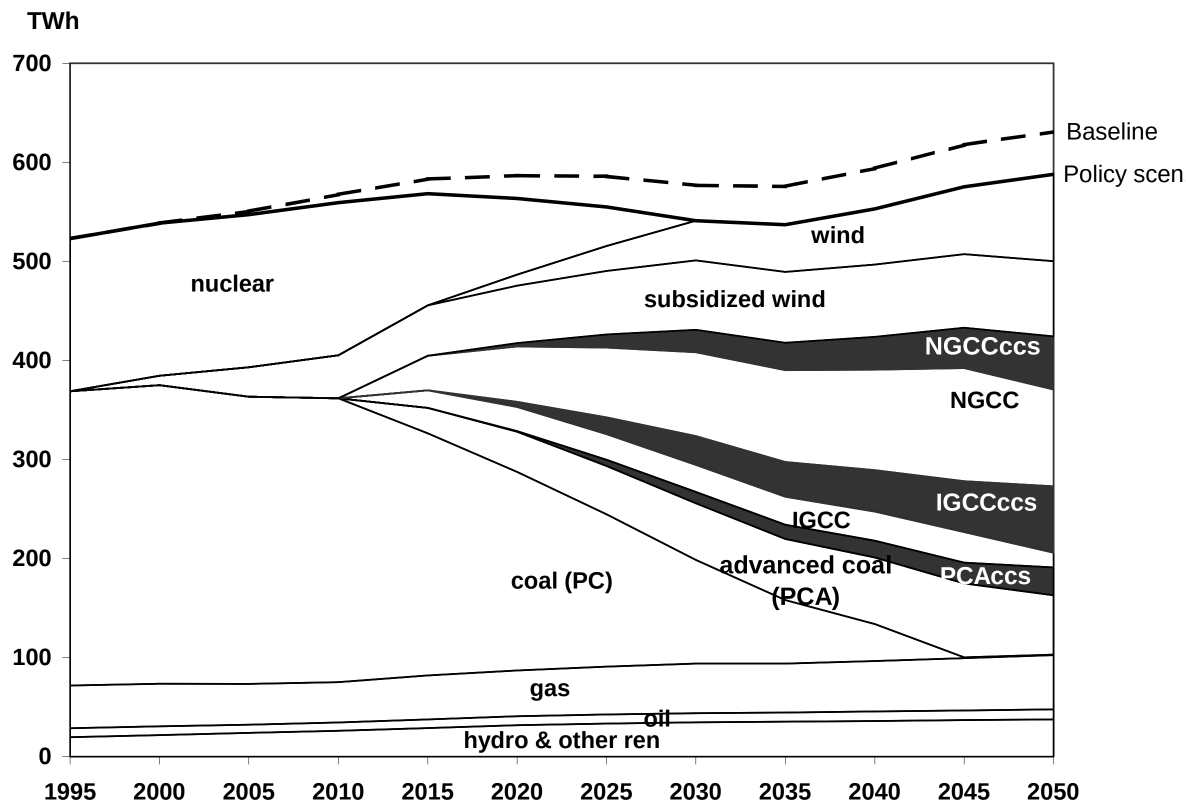


Figure 6 Electricity generation mix with a stepwise CO_2 price increase

4.2. Results for greenhouse gas emissions

Baseline projections for CO_2 (from SGM) and the non-CO_2 greenhouse gases (from German data sources) are shown in Figure 7a. Baseline emissions of CO_2 resulting from fossil fuel use decline in accordance with past data until 2005 and slowly rise again thereafter. Emissions of non-CO_2 gases show a future pattern consistent with past trends (compare section

2). CH_4 emissions continue to 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 and remain constant thereafter. Projections for the non-CO_2 gases are not available after 2030; therefore, baseline levels of non-CO_2 gases are held constant after 2030. Emissions of non-CO_2 greenhouse gases 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.

Figures 7b and 7c show simulated greenhouse gas emissions at CO_2–eq price scenarios of 20 € and 50 € respectively, targeted to those sectors that are covered under the EU emissions trading scheme. CO_2 prices follow the time paths shown in Table 4.1. Reductions in CO_2 emissions are derived from simulations with SGM Germany and include mitigation activities in form of fuel switching, output adjustment, efficiency improvement and inclusion of CCS in response to the CO_2 prices. By 2020, a 50 € price yields a 10% reduction of CO_2 emissions, which doubles to more than 20% by 2040.

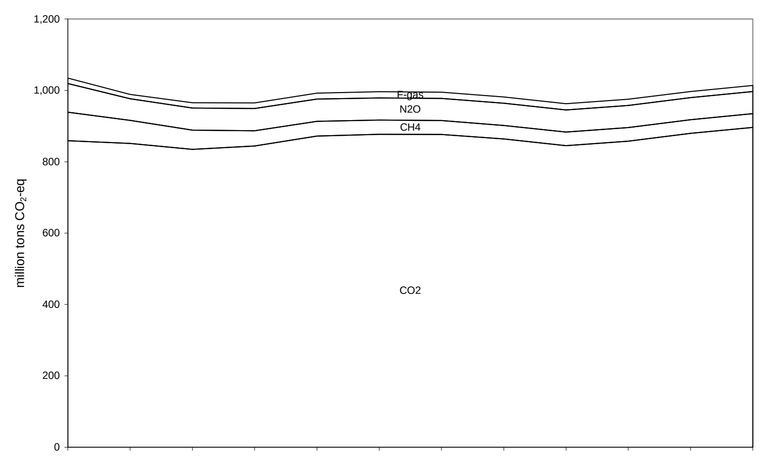


Figure 7a Greenhouse gas emissions pathway, baseline

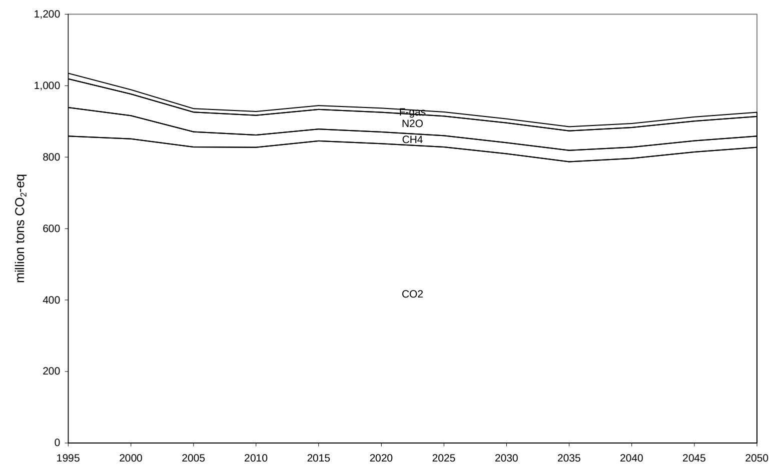


Figure 7b Greenhouse gas emissions pathway, 20 € per ton CO_2-eq

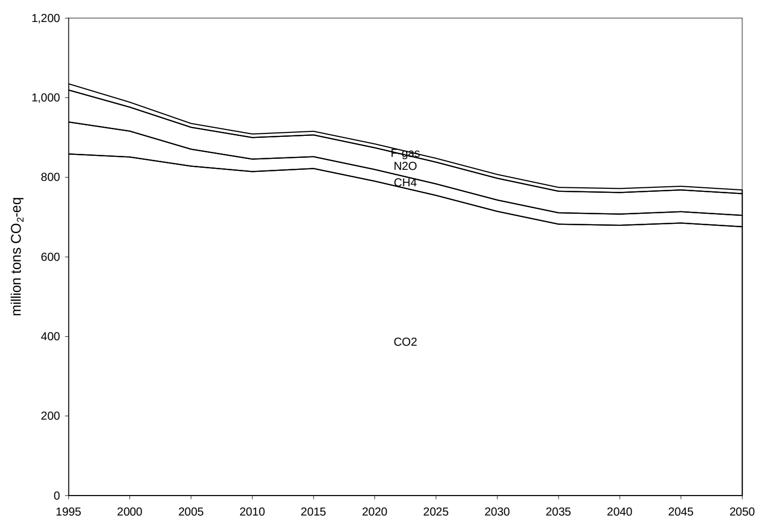


Figure 7c Greenhouse gas emissions pathway, 50 € per ton CO_2-eq

Reductions in greenhouse gas emissions other than CO_2, however, are less sensitive to a CO_2–eq price policy. Much of the mitigation potential is exhausted in the baseline with early reduction. Marginal abatement cost curves are applied to the remaining baseline emissions, by greenhouse gas (CH_4, N_2O, HFCs, PFCs, SF_6) and by activity within CH_4 and N_2O, to simulate a climate policy. The marginal abatement cost curves are used as look-up tables to derive a percentage reduction in CO_2-eq emissions for any given price of CO_2.[3] The cost curves typically allow inexpensive emissions reductions up to a turning point, with further reductions very expensive. Most reductions in non-CO_2 greenhouse gas emissions beyond the baseline occur at CO_2-eq prices below 20 €.

4.3. Economic comparison

For any selected year, we can express emissions reduction potential in the form of a marginal abatement cost curve with separate components representing greenhouse gas mitigation options. An example is shown in Figure 8 for year 2040. The mitigation components are: economic activity (a small loss in economic output due to climate policy); product mix (a shift away from energy-intensive industries); energy intensity (changes in energy consumed per unit of output); fuel mix (changes in the share of fuels used by each industry); changes in CO_2 emissions coefficients (which apply only to carbon dioxide capture and storage in electricity); and reduction in emissions of 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.

For each of the six components, we derive its contribution to the overall marginal abatement cost curve by conducting a set of CO_2-eq price scenarios and determining the reduction in emissions relative to the baseline. The component of non-CO_2 greenhouse gas emissions reductions is calculated based on exogenous information as described in the previous section. The other five components are calculated using the logarithmic mean Divisia index

[3] The U.S. Environmental Protection Agency provided marginal abatement cost curves to the Stanford Energy Modeling Forum as discrete points defining a piecewise-linear supply curve. We fit a smooth curve to these points using an exponential functional form.

(LMDI) method as described in Ang (2005). Using notation from Ang (2005), we can write total CO_2 emissions across all industries as

$$C = \sum_i \sum_j C_{ij} = Q \sum_i \frac{Q_i}{Q} \frac{E_i}{Q_i} \sum_j \frac{E_{ij}}{E_i} \frac{C_{ij}}{E_{ij}} \tag{1}$$

where C is total industrial CO_2 emissions and C_{ij} is the emissions from fuel j in industrial sector i. Q is a measure of total industrial activity, in this case the sum of gross output Q_i across industrial sectors. E_i is total energy consumed in sector i, and is the sum across fuels E_{ij} consumed in that sector. The ratio of C_{ij} to E_{ij} is a CO_2 emissions coefficient; which is constant for each fuel except for the case of carbon dioxide capture and storage (CCS) in electricity generation.

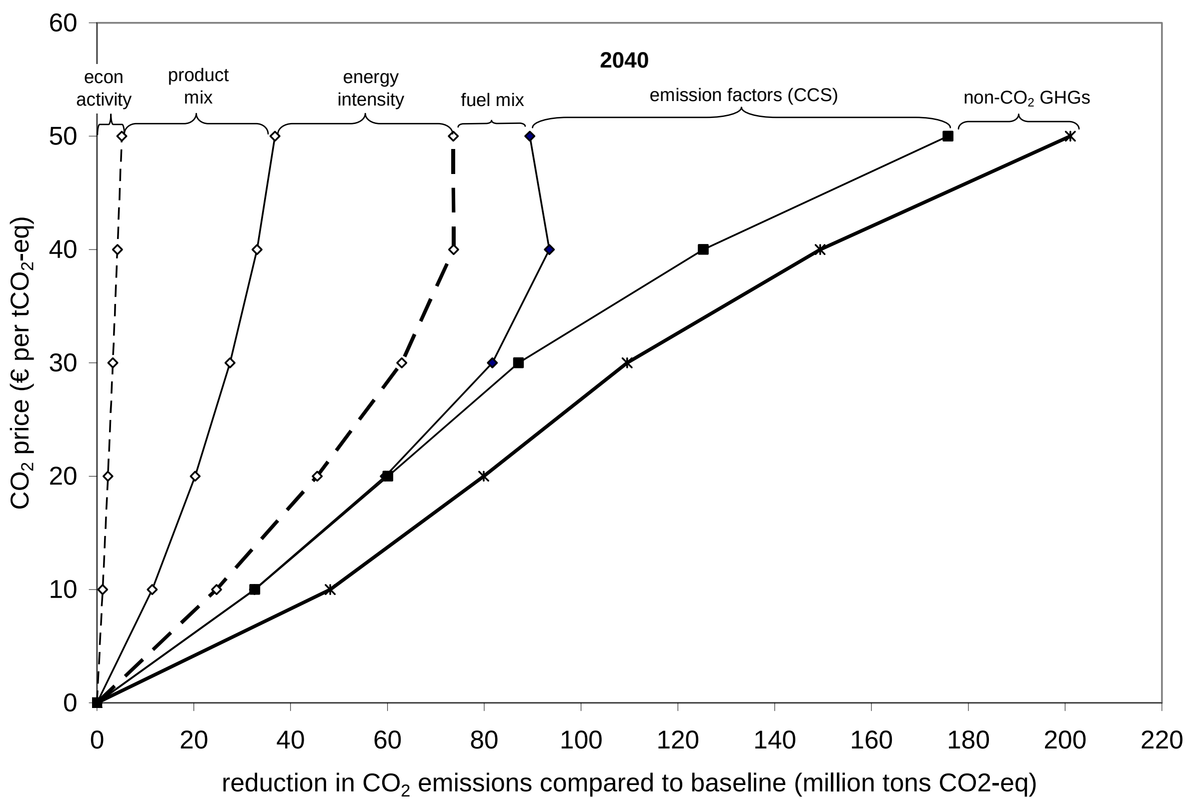


Figure 8 Simulated emissions reductions over a range of CO_2 prices, Germany 2040

The LMDI decomposition is used to express changes in CO_2 emissions, either over time or across scenarios at a point in time, as the sum of five explanatory components. In this case, we construct decompositions across a reference scenario and several CO_2-eq price scenarios using model output for year 2040. See Ang (2005, Table 8) for the decomposition algorithms.

Although we generated this set of marginal abatement cost curves with a number of constant CO_2-eq price scenarios, they correspond to the marginal abatement cost curves that would result for a national emissions trading system with a given target. This means that for any given reduction target the curves reveal the implied marginal costs (CO_2 price) and the set of mitigation options employed.

From Figure 8, we see that the economic activity and product mix components increase gradually with the CO_2 price. The economic activity component reflects reduced emissions from a small reduction (less than 1%) in gross domestic product with the carbon policy. The product mix component is a reduction in emissions due to shifts in production away from energy-intensive industries and toward other sectors.

CCS is not available at low CO_2 prices, but can be a significant contributor to emissions reduction at CO_2 prices above 30 € per ton. For each electricity-generating technology that can use CCS, we 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.

The energy intensity and fuel mix components increase gradually up to a CO_2-eq price of 40 € per ton. At this price point, carbon dioxide capture and storage becomes a large share of emissions reduction, and there are some interactions between the CCS, energy intensity, and fuel switching components.

The non-CO_2 greenhouse 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.

Figures 8 provided a decomposition of the change in CO_2 emissions between a reference scenario and a policy scenario *at a point in time* (year 2040). One can also construct decompositions of changes in emissions *over time*, for a single scenario. A decomposition over time can look very different than at a point in time. Figure 9 provides a decomposition over time for industry-wide CO_2 emissions. This decomposition is for the stepwise policy scenario relative to the base year of 1995.

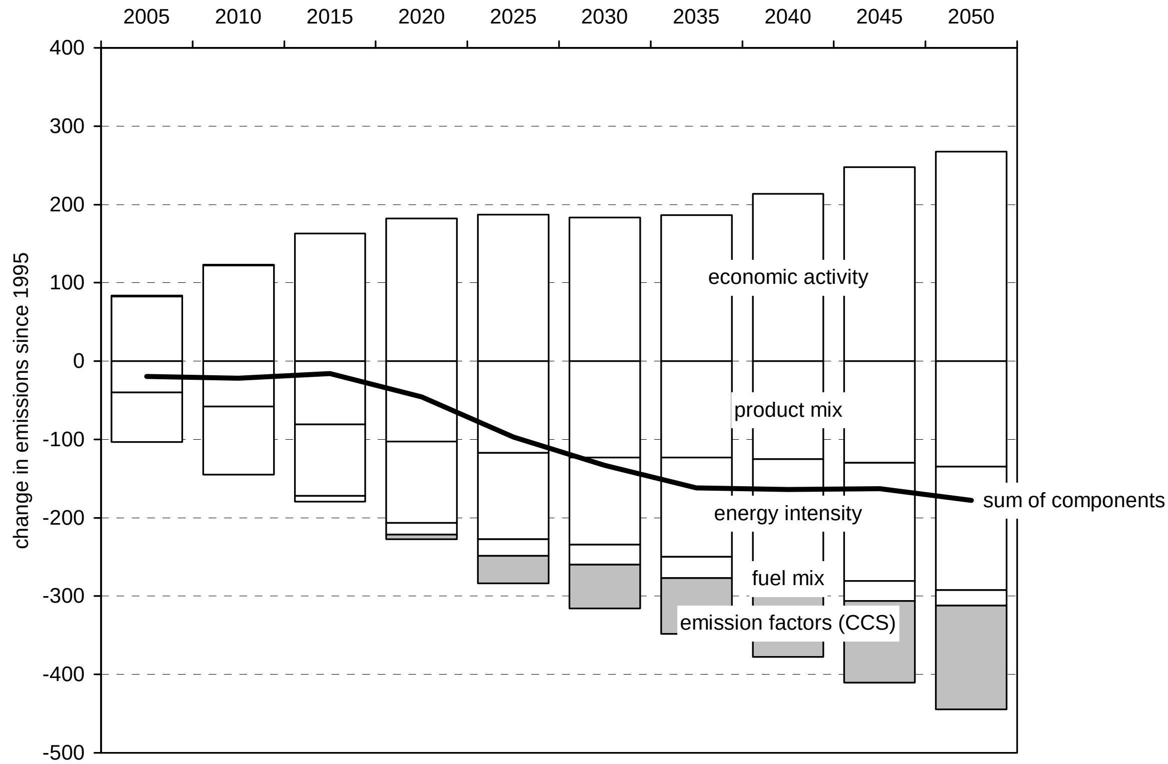


Figure 9 Decomposition of industrial CO_2 emissions (including electricity) over time, relative to model base year (1995)

The greatest difference between Figures 8 and 9 is the magnitude and sign of the economic activity component. In the decomposition at a point in time, there is a small reduction in economic activity between the baseline scenario and the policy scenario. Over time, there are large gains in economic activity but also large offsetting components due to changes in product mix and energy intensity for a net reduction relative to the base year.

It turns out that the electricity generation sector provides more than half of the emissions reductions at higher CO_2 prices and we provide a separate decomposition for the electricity sector in Figure 10. This electricity decomposition differs from that used in Figure 8; the fuel mix component is replaced with a generation mix component and we now have a CCS energy penalty component. This decomposition helps explain the interaction of CCS with other components and takes advantage of model structure with many electricity-generating technologies. In this case, electricity sector CO_2 emissions can be written as

$$C_{elec} = \sum_k C_{elec,k} = Q \frac{Q_{elec}}{Q} \sum_k \frac{Q_{elec,k}}{Q_{elec}} \frac{E_{elec,k}}{Q_{elec,k}} \frac{C_{elec,k}}{E_{elec,k}} \tag{2}$$

where *k* is an index over technology group (oil-fired, coal-fired, gas-fired, nuclear, renewables). The term $Q_{elec,k}/Q_{elec}$ represents generation mix, and $E_{elec,k}/Q_{elec,k}$ is the ratio of energy consumption to kWh generated and is a true energy efficiency indicator.

The energy efficiency component turns out to have the opposite sign as the other components, at least with CO_2 prices high enough to provide an incentive for CCS. At low CO_2 prices, the efficiency component vanishes. This component represents the energy penalty for capturing and storing CO_2; more energy is needed as an input to electricity generation for each net kWh generated. The CCS component in Figure 10 represents the amount of CO_2 captured and stored; however, its contribution to emissions reduction is partiallyoffset by the energy penalty component. Figure 10 contains components of opposite sign, so emissions reductions are now shown as negative changes, while the energy penalty is shown as an emissions increase.

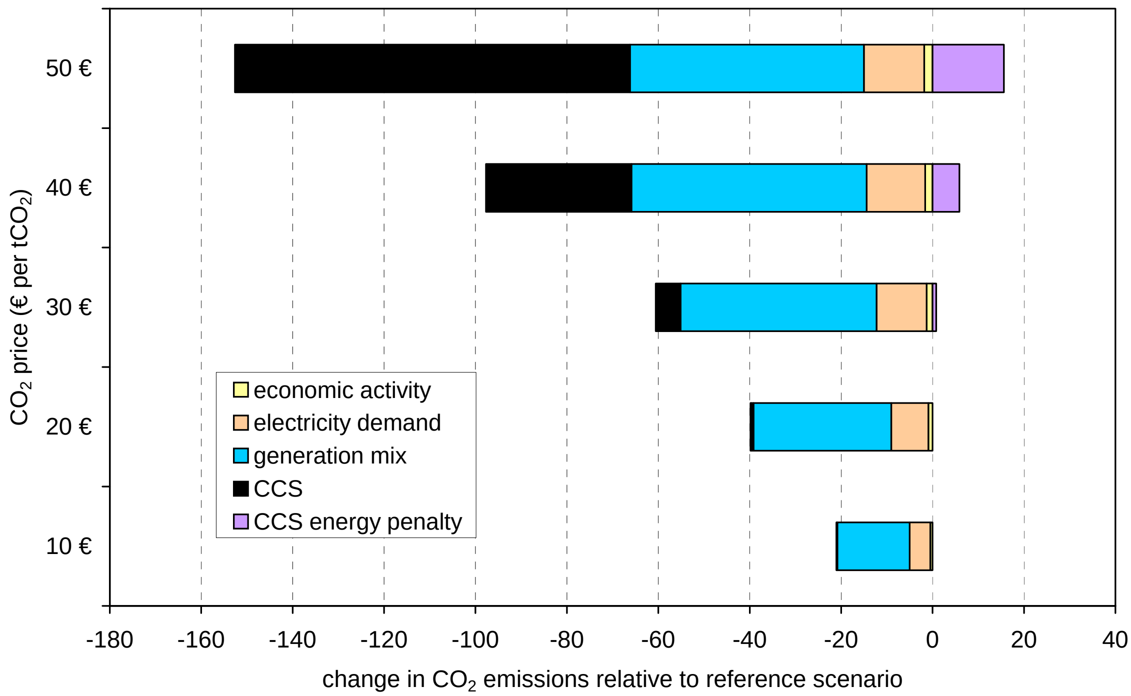


Figure 10 Decomposition of electricity sector CO_2 emissions in 2040

This alternative decomposition, Equation (2), replaces the fuel mix component with a generation mix component, and represents a large share of emissions reduction in electricity generation. The generation mix component includes fuel switching, such as a shift from coal to natural gas as a fuel, but it also includes a shift toward wind power. The electricity demand component represents a decreased amount of electricity demanded by other sectors, as those sectors adjust to higher electricity prices with a climate policy.

We also construct a decomposition of CO_2 emissions over time for the electricity sector as shown in Figure 11. Again, the greatest difference between the over-time and point-in-time decompositions is the sign and magnitude of the economic activity component. If electricity generation increased at the same rate as the industrial economy, then electricity generation would increase substantially over time. However, the offsetting components result in a net reduction of CO2 emissions over time in electricity generation.

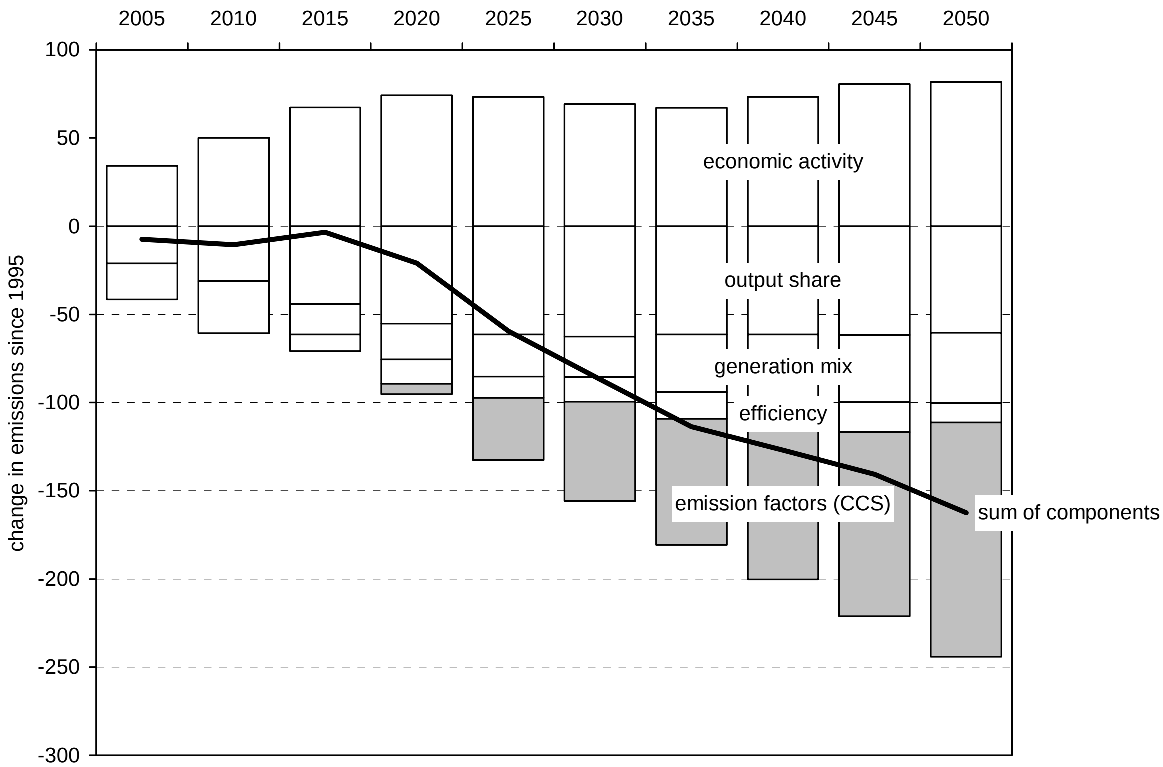


Figure 11 Decomposition of electricity sector CO_2 emissions over time, relative to model base year (1995)

To summarize, the analysis shows that mitigation options respond to a CO_2 price policy with varying degrees of sensitivity. Initially, non CO_2-GHG mitigation and energy efficiency improvement play the dominant role in achieving emissions reductions in response to a CO_2 price. An increase in energy efficiency is stimulated already at low levels of CO_2 prices and depends on the development of energy prices as well as relative prices of goods and inputs. As time moves on and new technologies become competitively available at a higher CO_2 price an increasing share is taken up by fuel switching, mainly driven by changes in the electricity generation mix as outlined above. Similarly, CCS technologies become economically competitive at prices above 30 € per ton of CO_2.

4.4. From partial to full coverage of economy

In a second set of results, referred to as full coverage, CO_2 incentives are applied to all sectors of the economy. Previously, the CO_2 incentive was applied only to energy intensive industries and electricity production. The CO_2 price is introduced to all sectors in 2005 at 10 € per ton of CO_2-eq and increased by 10 € every five years until a maximum of 50 € in 2025. With all sectors of the economy exposed to the CO_2 price scheme, the resulting aggregate CO_2–eq emissions reductions are greater than in the partial coverage case.

Figure 12 shows the distribution of emissions reductions across different mitigation options for the two cases, full and partial coverage, with a stepwise CO_2 price increase. The decompositions in Figure 12 compare a reference scenario with a stepwise policy scenario, at different points in time. The deviation from baseline increases over time as old capital is retired. This decomposition is based on seven components: the five components in Equation (1), a non-CO_2 greenhouse gas component, and a component for households. The largest difference between the full and the partial coverage case can be seen in emissions reductions that result from the consumer and energy efficiency components. The product mix component increases slightly.

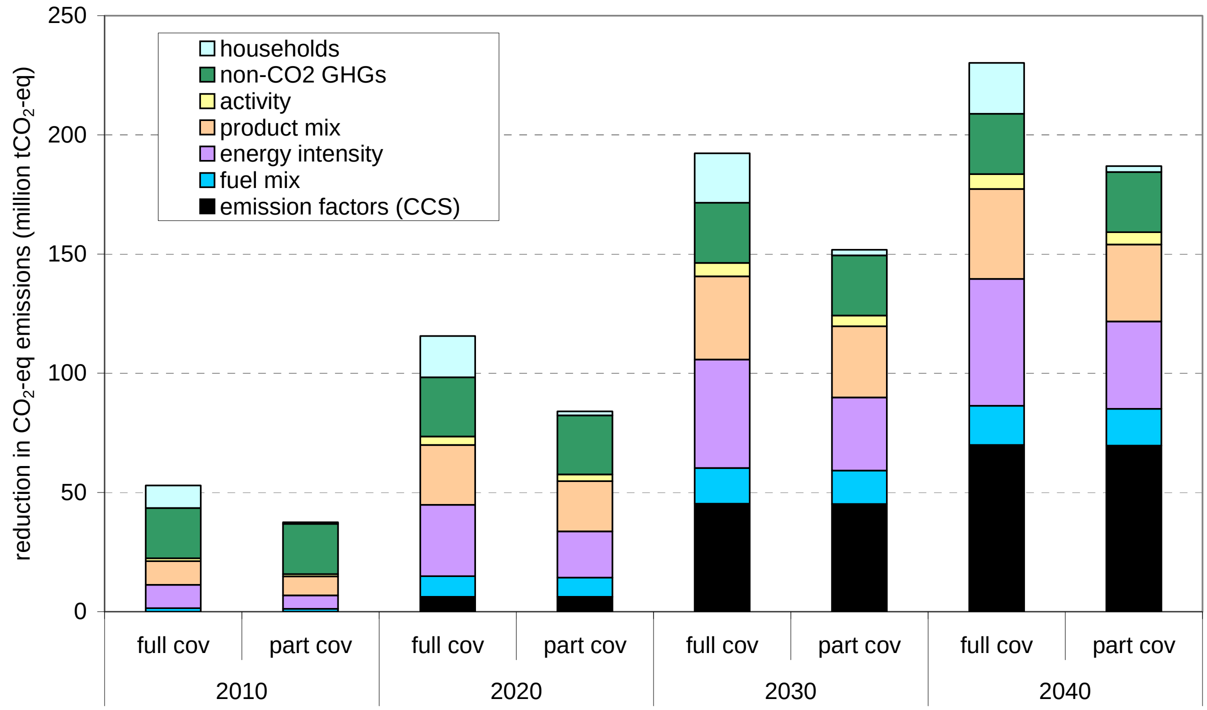


Figure 12 Decomposition of emissions reduction with a stepwise increasing CO_2 price fully and partially covering the economy

The contribution to emissions reduction from the household sector increases along with the CO_2 price. Even though households are not taxed directly in the partial-coverage scenario, there remains a small reduction in emissions. This is an indirect effect through electricity prices and consumption of other goods that are taxed.

The energy efficiency component is larger with full coverage because more sectors of the economy shift their input structure from energy inputs toward other inputs. Even though these sectors, such as services, are not as energy-intensive, they represent a large part of the economy.

5. 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 climate 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 climate 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 because of fuel switching and introduction of CCS.

This study is one step toward providing more realistic scenarios of greenhouse gas mitigation options in Germany. Future efforts could involve a more refined decomposition of the energy intensity and fuel shift components into production efficiency and technology shift. We have done this for the electricity sector but not for other sectors. Future work might also capture the impact of international trade. For example, a change in product mix may imply a shift in production and emissions activities to other countries or regions (often referred to as leakage effect). Furthermore, this research could be extended to include an endogenous representation of mitigation options in non-CO_2 greenhouse gas emissions. This would include to have available Germany specific abatement options and costs, and to include them directly, as a function of economic activity, in the analysis. Another possible extension is an analysis of the potential for biofuels, which become more cost-effective with higher oil prices and CO_2 prices.

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