

INNOVATIVE ENERGY TECHNOLOGIES IN ENERGY- ECONOMY MODELS

Assessing economic, energy and environmental impacts of climate policy
and technological change in Germany

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Abstract

Energy technologies and innovation are considered to play a crucial role in climate change mitigation. Yet, the representation of technologies in energy-economy models, which are used extensively to analyze the economic, energy and environmental impacts of alternative energy and climate policies, is rather limited. This dissertation presents advanced techniques of including technological innovations in energy-economy computable general equilibrium (CGE) models. New methods are explored and applied for improving the realism of energy production and consumption in such top-down models. The dissertation addresses some of the main criticism of general equilibrium models in the field of energy and climate policy analysis: The lack of detailed sectoral and technical disaggregation, the restricted view on innovation and technological change, and the lack of extended greenhouse gas mitigation options. The dissertation reflects on the questions of (1) how to introduce innovation and technological change in a computable general equilibrium model as well as (2) what additional and policy relevant information is gained from using these methodologies. Employing a new hybrid approach of incorporating technology-specific information for electricity generation and iron and steel production in a dynamic multi-sector computable equilibrium model it can be concluded that technology-specific effects are crucial for the economic assessment of climate policy, in particular the effects relating to process shifts and fuel input structure. Additionally, the dissertation shows that learning-by-doing in renewable energy takes place in the renewable electricity sector but is equally important in upstream sectors that produce technologies, i.e. machinery and equipment, for renewable electricity generation. The differentiation of learning effects in export sectors, such as renewable energy technologies, matters for the economic assessment of climate policies because of effects on international competitiveness and economic output.

Keywords: Energy technologies, electricity generation, iron and steel production, technological change, learning-by-doing, general equilibrium modelling, hybrid modelling, climate policy, international trade.

Zusammenfassung

Die Einführung neuartiger Energietechnologien wird allgemein als der Schlüssel zur Senkung klimaschädlicher Treibhausgase angesehen. Allerdings ist die Abbildung derartiger Technologien in numerischen Modellen zur Simulation und ökonomischen Analyse von energie- und klimaschutzpolitischen Maßnahmen vielfach noch rudimentär. Die Dissertation entwickelt neue Ansätze zur Einbindung von technologischen Innovationen in energie-ökonomische allgemeine Gleichgewichtsmodelle, mit dem Ziel den Energiesektor realitätsnäher abzubilden. Die Dissertation adressiert einige der Hauptkritikpunkte an allgemeinen Gleichgewichtsmodellen zur Analyse von Energie- und Klimapolitik: Die fehlende sektorale und technologische Disaggregation, die beschränkte Darstellung von technologischem Fortschritt, und das Fehlen von einem weiten Spektrum an Treibhausgasminderungsoptionen. Die Dissertation widmet sich zwei Hauptfragen: (1) Wie können technologische Innovationen in allgemeine Gleichgewichtsmodelle eingebettet werden? (2) Welche zusätzlichen und politikrelevanten Informationen lassen sich durch diese methodischen Erweiterungen gewinnen? Die Verwendung eines sogenannten Hybrid-Ansatzes, in dem neuartige Technologien für Stromerzeugung und Eisen- und Stahlherstellung in ein dynamisch multi-sektorales CGE Modell eingebettet werden, zeigt, dass technologiespezifische Effekte von großer Bedeutung sind für die ökonomische Analyse von Klimaschutzmaßnahmen, insbesondere die Effekte hinsichtlich von Technologiewechsel und dadurch bedingten Änderungen der Input- und Emissionsstrukturen. Darüber hinaus zeigt die Dissertation, dass Lerneffekte auf verschiedenen Stufen der Produktionskette abgebildet werden müssen: Für regenerative Energien, zum Beispiel, nicht nur bei der Anwendung von Stromerzeugungsanlagen, sondern ebenso auf der vorgelagerten Produktionsstufe bei der Herstellung dieser Anlagen. Die differenzierte Abbildung von Lerneffekten in Exportsektoren, wie zum Beispiel Windanlagen, verändert die Wirtschaftlichkeit und die Wettbewerbsfähigkeit und hat wichtige Implikationen für die ökonomische Analyse von Klimapolitik.

Schlagwörter: Energietechnologien, Stromerzeugung, Eisen- und Stahlproduktion, technologischer Wandel, Lerneffekte, allgemeine Gleichgewichtsmodelle, Hybridmodellierung, Klimapolitik, internationaler Handel.

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1 Introduction

In the last decade, growing attention has been paid to global warming, its causes and potential impacts. Most recently, the Intergovernmental Panel on Climate Change reported that significant climate change due to the accumulation of anthropogenic greenhouse gases in the atmosphere is very likely to take place¹ (IPCC, 2007). Substantial emissions reductions are needed to avoid potentially dangerous interference with the global climate. How such emissions reductions could be achieved and what economic costs and benefits it would imply is a matter of controversy among researchers around the world. However, the importance of innovative technologies in achieving deep cuts of emissions is undisputed. Often, technologies are thought to be the magic bullet for mitigation.

Understanding technological change is essential to generate effective options to curb emissions (Houghton, 2006). The availability, development, nature, and potential of innovations highly influence the effectiveness and economic efficiency of climate change mitigation. Energy innovations that enable or facilitate the reduction of carbon intensive energy use may substantially contribute to mitigation efforts. These include innovations for (1) energy conservation and energy efficiency improvement²; (2) fuel switching towards carbon free or low carbon energy, such as renewable energy; (3) technology switching towards low or no CO₂ emitting systems; (4) carbon waste management, such as carbon capture and storage.

Technological change may relate to the development of new technologies or to the accelerated diffusion of already existing technologies. Innovation may be of radical nature, i.e. lead to fundamentally new products or processes, or of incremental nature, i.e. improve the concept or performance of existing sets of technologies. In either case, it implies substantial changes in the character of economic activity (Sue Wing, 2006a).

Many potential innovations do not reach technical maturity or do not pass the diffusion and adoption step and do not gain a market impact. Climate policy can help to bring innovations into the market. However, this has to be done in a cost efficient way with regard to the impact on the whole economy.

¹ In IPCC terminology, ‘very likely’ means a greater than 90 per cent probability of occurrence.

² In the literature, the term energy efficiency is often broadly used. It may encompass everything from pure efficiency increase (reduced use of one or all inputs) to fuel switching, output adjustment and sectoral shifts in the economy, i.e. it may include (1) and (2) of the above.

Understanding the effectiveness and costs of policy measures, and their success in shifting energy systems toward more environmentally desirable technology paths has been a challenge taken on, among others, by climate and energy-economy-environment policy modelers (Hourcade et al., 2006). In this dissertation, I explore innovative ways of including technological change in the framework of energy-economy models. I illustrate new approaches of treating technology innovations and apply these approaches to analyze the impacts of climate policy and innovation on economic activity, including energy supply and demand, and associated environmental effects. The following sections of this introduction provide important concepts and terminology with respect to modeling approaches and inclusion of technological change and place my research within the literature.

1.1 Energy-economy-environment modeling

An increasing number of empirical models have been developed to analyze economic and environmental impacts of policy measures (Löscherl, 2004), relying on different methodological approaches and addressing different foci. They can be divided into two main types of model approaches, bottom-up and top-down approaches, and differ with respect to the emphasis paid to including detailed, technology-based information of the energy system and including theoretically consistent descriptions of the general economy (Löscherl, 2004). A discussion and survey of the specific features, advantages, weaknesses and caveats of each of the two approaches can be found in e.g. Bataille et al. (2006), Hourcade et al. (2006), Löscherl (2002, 2004), Weyant and Olavson (1999).

Bottom-up models represent entire energy systems in terms of specific technologies. They simulate (or optimize) the operation of specific energy technologies based on cost and performance characteristics in a partial (equilibrium) framework. They contain detail on current and future technological options and describe competition of these technologies both on the energy supply side and on the energy demand side. Because of their technology focus and the possibility of accounting for fundamentally different technology pathways they can provide detailed information on environmental impacts for each path. However, bottom-up models lack interaction with the rest of the economy and rely on exogenous assumption about the scale of future energy demand (Grubb et al., 2006; Löscherl, 2002). They do not include information on producers' or consumers' decision-making and, consequently, do not provide information on the behavioral aspects of the technology selection process. In addition, they are not linked to include feedback from macroeconomic variables, such as economic growth,

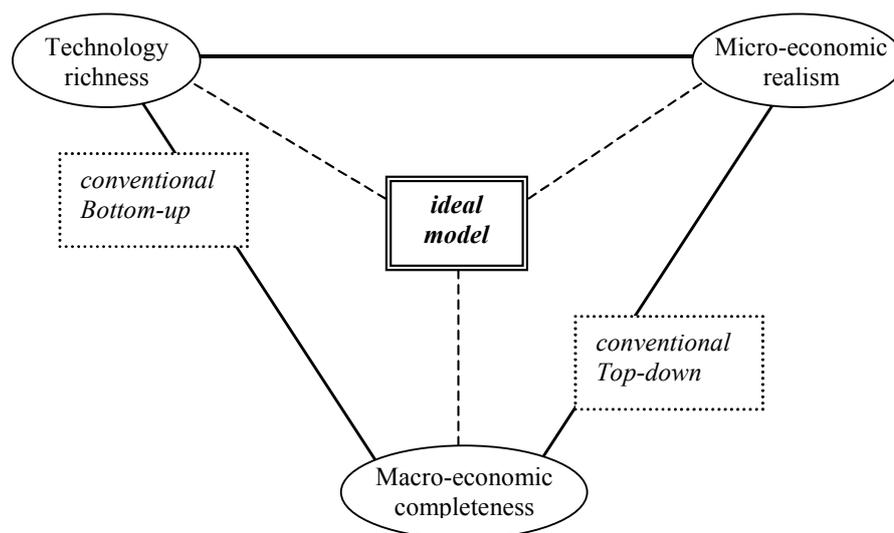
economic structure, energy demand, and international trade. These parameters may change in response to energy and climate policies, which in turn would affect decision-making and technology selection and, subsequently, environmental impacts (Hourcade et al., 2006).

Top-down models, on the other hand, use a broader economic framework. Models of the top-down type are commonly called energy-economy models and include macro-econometric models, optimal growth models and dominantly computable general equilibrium (CGE) models. These models represent economic responsiveness to policies and account for feedbacks in form of for example input substitution, structural change, output adjustment, and trade effects. However, in order to include behavioral and other non-technical factors such as policy instruments, they usually compromise on the level of technology detail, which may be relevant for an appropriate assessment of energy or climate policies (Jaffe et al., 2003; Edmonds et al., 2001). Moreover, technology choice is usually constrained to current practice and substitution elasticities are calibrated to base year information or, in the case of econometric models, estimated based on historical data. These parameters, however, may change in the future in response to the availability of new technologies with their inherent characteristics and in response to new environmental policies. Most top-down models are not able to cope with such radical or even incremental changes, and their simulations into the future (baselines) remain bound to the behavioral and technical structure of the base year or past trends.

The divergence between the two model types became evident when the policy debate shifted towards the economic and technology analysis of reducing greenhouse gas emissions. It turned out that top-down models reveal high costs of greenhouse gas emissions mitigation because they assume that economic markets are in equilibrium and any deviation from this equilibrium imposes costs to the economy. This means they exclude the existence of inefficiencies and, thus, of energy efficiency potentials that could be profitably realized (Hourcade et al., 2006; Bataille et al., 2006). On the other hand, bottom-up models reveal ‘no-regret’ or low cost options to mitigate greenhouse gases because of their technology and efficiency improvement perspective and implicit assumption of the existence of market imperfections. They fail to include (transaction) costs related to removing such market imperfections. Market imperfections may be due to imperfect information, limited financial markets, technology-specific risks, inertia in technology preferences, behavioral change in response to efficiency gains (rebound effects), and more (Hourcade et al., 2006; Löschel, 2002, 2004). The divergent views on the economics of efficiency improvement potentials are

often referred to as the 'efficiency gap' and have been intensely discussed in the literature (Grubb et al., 1993).

An 'ideal' model would couple all sets of information, either in form of hard-linking different model types or in providing a model that incorporates all features, and would perform well in all categories depicted in Figure 1.1. It would be technologically explicit in the full range of activities, consider supporting upstream and downstream technologies, and cover the evolution of technologies and underlying risks and uncertainties (Jacoby et al., 2006; Hourcade et al., 2006; Bataille et al., 2006). Moreover, it would be behaviorally realistic in terms of micro-economic detail and it would include (macro)economic feedbacks, in linking changes in relative costs of goods and services to their supply and demand, as well as balancing budgets and markets.



Source: Adapted from Hourcade et al. (2006)

Figure 1.1 Energy-economy-environment models

To compensate for the limitations of either of the two approaches, hybrid models have been developed that incorporate features from one model type into the other and aim at combining features of both model types. Bottom-up modelers, usually with a background in engineering, physics or environmental sciences, add macro-economic feedbacks into their models or include micro-economic decision-making. Examples are extensions of the MARKAL optimization model, e.g. MARKAL-MACRO (Manne and Wene, 1992) which

adds a growth model and economy-wide production functions to the MARKAL model, or MARKAL-ED (Loulou and Lavigne, 1996) which adds demand elasticities for some key products. A similar approach is followed in MERGE (Manne et al., 1995). In the MESSAGE-MAKRO model, an energy system model is solved in an iterative process with an economy model allowing for feedbacks between the two models (Rao et al., 2006). Another hybrid approach is demonstrated in the CIMS model, which also iterates between energy demand, energy supply, and macroeconomic modules (Bataille et al., 2006; Jaccard et al., 2003).

Top-down modelers, usually with a background in economics, devote efforts to adding explicit technological modules to their models, permitting a choice between these technologies and allowing for shifts in technology characteristics over time towards best practice innovative technologies (Schumacher and Sands, 2006, 2007; Edenhofer et al., 2006; Sands, 2004; McFarland et al., 2004, 2006; Welsch, 1998, 1996). Jacobsen (2000) employs a top-down macro-econometric model to incorporate the diffusion of energy technologies of different vintages associated with different levels of efficiency. Recent efforts devoted to coupling detailed energy models, such as MARKAL, with CGE frameworks include those by Schäfer and Jacoby (2006, 2005) for transport technologies and by Proost and van Regemorter (2000) for energy services. Using advanced mathematical techniques, Böhringer (1998) and Böhringer and Löschel (2006) demonstrate an approach of linking a CGE model with bottom-up activity analysis for electricity generation while other sectors are represented by conventional functional forms used in top-down analysis. Apart from theoretical, analytical as well as computational complexities of combining the two approaches, or features thereof, another important difficulty is to construct an integrated database. Engineering and economic data are most often not consistent and calibration of a model based on both types of datasets remains a challenge (Sue Wing, 2006).

A lesson learned from both model approaches is the importance of technologies, and changes thereof, for the assessment of mitigation costs and options. Independent of the modeling approach the assumptions about technology play a crucial role (Löschel, 2004). Therefore, I turn to a more detailed view on the inclusion of innovation and technological change in energy-economy-environment modeling.

1.2 Innovation and technological change in energy-economy-environment models

There are different ways of incorporating innovation and technical change in energy-economy-environment models. Up to the late 1990s, most models have been rather weak at this issue (Nemet, 2006). Technologies and technological change were incorporated through exogenous assumptions. In top-down models, changes in technologies were reflected as a result of changes in relative prices through assumptions about elasticity of substitution between input factors.³ In addition, an autonomous energy efficiency improvement (AEEI) parameter was used to reflect an increase in efficiency independent of changes in prices or economic behavior (Grubb et al., 2006).⁴ Thus, the AEEI subsumes (exogenous) diffusion of new and efficient technologies or 'from heaven' changes in structural relationships. It implies a continuous, steady and incremental improvement and does not allow for radical innovations (Sue Wing, 2006). The concept of an autonomous efficiency improvement indicator is rather limited because the rate and direction of technological change are specified exogenously and are independent of the effects of changes in policy or other model variables. For policy analysis, this implies that substitution between inputs and output reduction are the only ways that input demand can be affected by policy measures. In contrast, penetration of technologies in bottom-up approaches is modeled using cost and performance characteristics of actual technologies. Technological change occurs as one technology is replaced with another, thus allowing for radical changes in technologies but still relying on exogenous assumptions on technology characteristics (Löschel, 2004).

Apart from the development of hybrid modeling approaches (compare section 1.1), which evolved in response to these criticisms, each community of modelers in itself realized that an enhanced treatment of innovations and technological change was needed to meaningfully evaluate the cost of climate and energy policies. Also, it was acknowledged that the rate and direction of future technological change impose high uncertainties for these evaluations (Edenhofer et al., 2006a). Consequently, modelers attempt to incorporate lessons from the literature on the economics of innovation and endogenous growth theory and seek to endogenize technological change in their models (Köhler et al., 2006; Nemet, 2006).⁵

³ In economic terms, this refers to a shift in input use along the unit isoquant.

⁴ In economic terms, it represents an inward shift of the unit isoquant.

⁵ To date, there is still a lag between state of the art research in the economics of innovation and in economic modeling of innovation, which may be explained by a number of incompatibilities of the methodological approaches (Köhler et al., 2006; Nemet, 2006). For example, the economics of innovation emphasizes the impact

Following Clarke et al. (2006a) endogenous technological change refers to technological change that depends – at least in part – on the development of particular socio-economic model variables like prices, investment in research and development, or cumulative production.⁶ The treatment of technological change became more sophisticated also because of increased computer power and improved algorithms to work with diverse phenomena (such as increasing returns) (Grubb et al., 2002).

A number of survey papers discuss the different treatment of technological change in economic and engineering models used to analyze climate policy. With varying focus they discuss implementation techniques, theoretical background, and implications on energy consumption, costs of environmental policy and timing of abatement measures (Sue Wing, 2006; Clarke et al., 2006a; Vollebergh and Kemfert, 2005; Löschel, 2002, 2004; Goulder, 2004; van der Zwaan et al., 2002; Weyant and Olavson, 1999; Grübler et al., 1999, 1998; Azar and Dowlatabadi, 1999; within the Innovation Modeling Comparison Project see Köhler et al., 2006; Edenhofer et al., 2006a; within the Stanford Energy Modeling Forum project on Technology and Global Climate Change Policies, see Weyant, 2004). A common finding from these efforts is that technology matters and that technology itself is modified by climate policy. Different ways of modeling technological change include introducing (1) backstop technologies, (2) enhanced technology information in hybrid approaches (3) technology learning, e.g. learning-by-doing, (4) R&D based knowledge accumulation (stock of knowledge approach), and (5) spillovers.

(1) Backstop technologies refer to sometimes generic, sometimes specific discrete technologies that are assumed to be exogenously available at some point in time, at specific marginal costs and with fixed characteristics as to emissions or energy intensity. They are often used to represent radical technological change because new production techniques can be explicitly modeled, however, at varying levels of detail (Löschel, 2004; Sue Wing, 2006; Kemfert, 2002). In top-down simulations, a backstop technology is often assumed to be a

of uncertainty in heterogeneous firms and path dependent technological development, adoption, and diffusion, which are difficult to implement in a more stylized and aggregate applied economic model with its common assumption of a representative producer and consumer. (Köhler et al., 2006; Freeman and Louca, 2001). The literature on innovation is characterized by its richness of description, by case study approaches, and rigorous empirical observation (Nemet, 2006). It provides only a limited set of methods with which to assess changes in technologies. Optimization and simulation models, however, have to deal extensively with uncertainties relating to model parameters and, future development thereof, and require reliable quantitative estimates, which are difficult to arrive at.

⁶ In contrast, induced technological change refers to an alteration in technological change (additional or different technological change) in response to a (climate) policy or set of policies. Its focus, thus, lies on understanding the effects of specific policy measures.

simple, generic carbon free technology, which becomes economically competitive in future periods in response to rising production costs of conventional technologies due to resources scarcity or policy induced price increases (Popp, 2006, 2006a; Kemfert, 2002; Löschel, 2002). In bottom-up models backstop technologies are usually explicitly represented with complete technology descriptions and expert judgments on typically relatively high production costs (Sue Wing, 2006). Commonly, backstop technologies are assumed to be available to produce any amount of output at constant marginal cost. This may lead to so called bang-bang or flip-flop behavior in models, which means that the backstop technology takes over the entire production once it has become competitive. To alleviate this, modelers often put an ad-hoc constraint on the rate of penetration of the backstop technology, thus imposing imperfect substitutability on the output of the backstop and the conventional technology (Sue Wing, 2006a; Popp, 2006, 2006a). Another profound limitation of this approach is that backstop technologies are discrete technologies with fixed input/output structure and marginal costs. Technological change beyond the assumptions inherent in the backstop technology cannot be accounted for.

(2) Based on the same principle of emphasizing the role of advanced technologies, but much more elaborated in their methodological and technological set-up, hybrid approaches have been developed. As discussed in section 1.1, they aim to incorporate features from both top-down and bottom-up approaches to reveal a more realistic picture of the energy, environmental and economic effects of climate policy and technological change.

(3) The concept of technology learning is based on the observation that production costs or investment costs of a certain technology or product decrease with cumulated experience of producing it. Experience can be described in terms of cumulated production, output, sales or cumulative installed capacity. Often learning-by-doing is distinguished from learning-by-using or learning-by-researching. Whereas learning-by-doing refers to cost reductions that occur in connection with increasing experience in the production and installation of a specific technology, learning-by-using refers to cost reductions achieved by increased efficiency and experience in using a specific technology. Moreover, learning-by-researching refers to cost reductions that arise as a result of R&D activities (Löschel, 2002). The learning approach is probably the earliest and most popular approach (Messner, 1997; Goulder and Mathai 2000; van der Zwaan et al., 2002). It is typically favored by bottom-up modelers who take advantage of the technological detail inherent to their models and their extensive knowledge of technology characteristics and related costs. Recent bottom-up models include a great number

of different technologies for energy production and learning-by-doing for specific, selected technologies (Rao et al., 2006; Hedenus et al., 2006; Barreto, 2001; Seebregts et al., 2000).

Fewer studies so far have implemented learning effects into macroeconomic (top-down) models. They mainly differ with respect to the proxy/indicator for the activity which causes learning: i) cumulative installed capacity of a technology (Gerlagh, 2006; Gerlagh and van der Zwaan, 2003, 2004), ii) sectoral output (Rasmussen, 2001; Carraro and Galeotti, 1997), iii) sectoral capital stock (van Bergeijk et al., 1997), iv) sectoral labor input (Kverndokk et al., 2004), v) technological know-how (learning-by-researching) (Goulder and Mathai, 2000), or vi) a combination of these indicators such as the two-factor experience curve that takes into account cumulative capacity as well as cumulative R&D expenditure (Kouvaritakis et al., 2000, 2000a; Klaassen et al., 2005). Goulder and Mathai (2000) employ a formulation in which cost reduction due to learning is a function of cumulative abatement.

Most studies agree that learning effects are most pronounced for relatively new and fast growing technologies, e.g. non-fossil energy technologies, as an increase of cumulative experience can be more easily achieved (McDonald and Schrattenholzer, 2001). Thus, they separate fossil energy from non-fossil energy and analyze the effects of learning-by-doing in non-fossil energy goods, such as renewable energy (van der Zwaan et al., 2002). When technological progress is induced via learning-by-doing rather than by autonomous efficiency improvement, this has an impact on the costs and optimal timing of environmental policies and of investment, which is the focus of most of those studies.

A wide range of learning rate estimates for renewable energy can be found in the literature (Neij et al., 2004; Papineau, 2006; Junginger et al., 2005; Ibenholt, 2002; IEA, 2000). They differ because of varying assumptions with respect to time periods, cost measures (investment cost, levelized cost of electricity production, electricity or turbine price), experience measures (cumulated installed capacity, cumulative produced capacity, electricity generated), geographical area, system boundaries, data availability and quality, and estimation methods. Given these uncertainties, it comes at no surprise that modeler's conclusions from incorporating learning effects show a broad span of divergence.

In addition, the learning approaches suffer from other important limitations (compare Sue Wing, 2006): 1. In perfect foresight models (or optimization models) non-convexities are introduced by implementing learning effects, which can lead to multiple equilibria; 2. As with backstop technology models, penetration constraints for learning in form of upper bounds on capacity or investment rates need to be included. This implies that the trajectory of cost

reduction becomes exogenous; 3. There is lack of transparency of learning rate assumptions, in particular in bottom-up models with large numbers of technologies and activities; 4. To date the approach is still heuristic with no profound theoretical foundation; 5. The simple learning approach implies that technological change results from activity within one and the same industry, it does not take into account spillovers from other industries, upstream or downstream production steps or activities in other countries; 6. The learning-by-doing approach implies that innovation occurs as a costless side effect rather than resulting from costly investment in R&D. It therefore takes the character of a free lunch.

(4) The R&D based knowledge accumulation approach (or stock of knowledge approach) picks up on the latter criticism and presents a learning-by-searching process where technological change is a result of investment in research and development. The approach is based on the idea that there is a stock of 'knowledge', which accumulates in reaction to an economic activity such as R&D. This knowledge influences production possibilities (or sometimes also consumption). The stock of knowledge or human capital is generated through investment into research and development activities. Model parameters, such as price changes induced by policy measures, may lead to increased investment into the stock of knowledge capital with its subsequent effects on substitution possibilities and productivity (Edenhofer et al., 2006; Popp, 2006a, 2004; Kemfert, 2005; Buonanno et al., 2003; Goulder and Mathai, 2000; Nordhaus and Boyer, 2000; Goulder and Schneider, 1999). The approach completely endogenizes technological innovation in treating it as an economic activity, which depends on profit-maximizing decision making from economic agents. It suffers most from a lack of disaggregated data on R&D at the level of individual technologies.

Given the model structure and sectoral and technology detail, macroeconomic (top-down) modelers tend to focus on the R&D approach while the majority of engineering (bottom-up) modelers focus on implementing learning-by-doing. Recently, more and more efforts have been taken to simultaneously model both approaches and reveal effects on economic output, environment and energy based on both costly and costless increase in experience (Bosetti et al., 2006; Goulder and Mathai, 2000; Gerlagh and Lise, 2005; Goulder and Schneider, 1999). This is sometimes referred to as two-factor experience curves (Kouvaritakis et al., 2000; Klaassen et al., 2005).

(5) Another important aspect in modeling technological innovations are spillover effects from R&D investment or technology learning. The existence of spillover effects implies that innovations are not fully appropriable. Spillovers may take the form of positive externalities

such as R&D, knowledge, technology, and innovation transfer but also of negative externalities such as the transfer of emissions (carbon leakage) and environmental effects to other regions or countries (Otto et al., 2005; Jaffe et al., 2003; Grubb et al., 2002; Weyant and Olavson, 1999). Weyant and Olavson (1999) define technological spillovers as "any positive externality that results from purposeful investment in technological innovation or development". Such knowledge spillovers and the induced innovation and diffusion of new technologies have been intensively discussed in the literature. See for example Sijm (2004) for a thorough assessment of this issue.

The approaches outlined here are not mutually exclusive, but can be applied independently or in combination. Typically, efforts to an enhanced treatment of technological change do not attempt to make all technological change in the model endogenous but allow certain technologies or industries to change endogenously while others are still treated using an exogenous specification (Clarke et al., 2006a, 2006). For example, emerging, innovative energy sector technologies might be treated endogenously while other technologies and the rate of change in the economy as a whole remain exogenous. Jacoby et al. (2006) call for caution when introducing endogenous technological change in top-down computable general equilibrium (CGE) models, because of potential double counting. Double counting may occur because empirically estimated key elasticities (substitution elasticities, income elasticities) may already reflect a certain degree of endogenous change in technology based on the underlying data. Similarly, some technical change may be incorporated in specific assumptions on technical characteristics and changes thereof when introducing technology information into energy-economy models. Likewise, endogenous change may be included in assumptions on emissions factors.

Based on the approach(es) taken, implementation chosen, and in light of the challenges, uncertainty and limitation in data, parameters, and model solutions issues as well as in light of the raised strengths and limitations of each approach, researchers have found that endogenizing technical change leads to either reduced costs of climate change mitigation or increased costs. Almost all of the above-cited studies conclude that the implication of endogenizing technological change is large for both the optimal timing of mitigation measures and the costs of such policy measures. Clarke et al. (2006a) point out that "models are not meant for prediction but for enhanced understanding. [...] different approaches have important insights and stories to tell about how technology might evolve in the future and how it might be influenced by actions to address climate change or other environmental issues. At

the same time interpretation of model results and information for decision-making should be taken with care so not to over-extend the implications of modeling exercises". Overall, it is an enormous challenge to incorporate endogenous technological change from different sources, and most importantly complex and complementary interactions thereof (Clarke et al., 2006a).

1.3 Goal and structure of dissertation

In this dissertation, I pick up on the issues discussed above and present innovative ways of including innovation and technological change in energy-economy models. I illustrate two new approaches of treating technology innovations, and changes thereof, and provide four different applications of these approaches to analyze the impacts of climate policy and innovation on economic activity, energy transformation and consumption, and associated environmental impacts. This dissertation, thus, covers important methodological issues as well as policy relevant aspects of innovation and climate change mitigation. It reflects on the questions of (1) **how** to introduce innovation and technological change in a computable general equilibrium (CGE) model as well as (2) **what** additional and policy relevant information is gained from using these methodologies.

My dissertation follows a cumulative approach and provides four studies that are linked by addressing these questions. Two novel modeling approaches of technological change are developed and applied. First, a hybrid approach of incorporating technology specific information for energy supply in a dynamic multi-sector computable general equilibrium model (CGE) is used to analyze the economic, energy, and environmental consequences of mitigation policies. This approach is then extended to account for specific technology descriptions in energy-intensive production, as well as to provide a detailed comparative economic analysis of a broad range of greenhouse mitigation classes. The second approach implements learning-by-doing effects in upstream production sectors that produce machinery and equipment and deliver capital goods to the energy sector in a multi-region multi-sector dynamic CGE model.

The first approach developed in this dissertation, the hybrid approach, addresses the gap between bottom-up and top-down models. It introduces the richness of engineering characteristics of key technologies to a CGE model, yet allows for a full general equilibrium analysis of energy or climate policies. It works at an intermediate level of technology detail, between the traditional aggregate production functions of top-down models and the extensive technology detail used in bottom-up models. The approach permits a choice between several

technologies and allows for shifts in technology characteristics over time towards best practice, innovative technologies. Shifts in energy consumption, in response to changes in energy or CO₂ prices, are consistent with shifts between technologies. This is important for both baseline and policy scenarios. Allowing for shifts in discrete technologies provides flexibility for future technology development to be decoupled from the base year structure. Further, improvements in technology characteristics can be based directly on engineering knowledge and projections.

The second approach aims to provide more insights into the effects of technological change, in particular learning-by-doing, in industries that are not immediately affected by climate policy but are responsible for delivering capital goods used in the energy sector. It goes beyond the conventional way of introducing learning-by-doing in energy or electricity producing sectors by separating out the impact of learning-by-doing in economic activities that are located further up in the production chain (such as machinery and equipment that produce renewable energy technologies). Two main effects take place by introducing learning-by-doing in the upstream machinery and equipment industry. Firstly, learning-by-doing leads to a reduction of the unit costs of equipment, which will, via capital goods (investment), translate into reduced costs further down the production chain (e.g. in electricity generation). The second effect relates to international trade. Machinery and equipment technologies are produced for either domestic demand or for exports. Learning-by-doing induced by domestic policies may improve the competitiveness of domestic producers, lead to a higher demand for these technologies and result in higher learning effects with its subsequent effects on costs and prices. This increases the international competitiveness and stimulates national and international demand for this machinery and equipment technology, which then again would induce higher learning. An analysis of learning-by-doing effects in downstream production (e.g. electricity) alone is not able to take account of these international trade effects.

In the chapter 2 of this dissertation, the technology-based approach is introduced in a multi-sector dynamic computable general equilibrium (CGE) model for Germany, the Second Generation Model (SGM). The focus is placed on advanced electricity technologies and their role within a future German electricity system. This analysis is based on the recognition that substantial mitigation opportunities exist in the electricity sector through the introduction of advanced technologies. Therefore, it models the response of greenhouse gas emissions in Germany to various technology and carbon policy assumptions over the next few decades. In

particular, the analysis simulates the potential role of four advanced electricity technologies, advanced pulverized coal (PCA), coal integrated gasification combined cycle (IGCC), natural gas combined cycle (NGCC), with and without the option of carbon capture and storage (CCS), and wind power from the present through 2050. In the baseline scenario, all of the advanced technologies except CCS provide substantial contributions to electricity generation. CO₂ policy scenarios are conducted to provide an estimate of the cost of meeting an emissions target, and the share of emissions reductions available from the electricity generation sector.

The second study (chapter 3) provides an application of the technology-based approach to an energy-intensive production sector (iron and steel) and explores how this method can improve the realism of energy-intensive industries in top-down economic models. The SGM model is modified by replacing a conventional constant-elasticity-of-substitution (CES) production function with a set of specific technologies. The response of the iron and steel sector to a set of CO₂ price scenarios is investigated under the traditional production function approach in CGE models and an approach with separate technologies. The technology-based, integrated approach permits a choice between several technologies for producing iron and steel and allows for shifts in technology characteristics over time towards best practice, innovative technologies. In contrast to technology-based partial-equilibrium models, the general equilibrium framework allows us to analyze interactions between production sectors, for example between electricity generation and iron and steel production, investigate simultaneous economy-wide reactions and capture the main driving forces of greenhouse gas emissions reductions under a climate policy. It can be concluded that technology-specific effects are crucial for the economic assessment of climate policies, in particular the effects relating to process shifts and fuel input structure.

The third study (chapter 4) provides a systematic analysis of options to mitigate greenhouse gas emissions in Germany, across a variety of climate policy scenarios. At least four classes of greenhouse gas mitigation options are available: energy efficiency, fuel switching, CO₂ capture and storage, and reductions in emissions of non-CO₂ greenhouse gases. These options vary by cost, timing, and our ability to represent them in an economic analysis. The analysis is done with the Second Generation Model (SGM) and embodies energy and other greenhouse gas mitigation possibilities. Policy scenarios are formulated as a change in the levels of the price for greenhouse gas emissions, either applied economy-wide or targeted at energy-intensive sectors of the economy according to the EU emissions trading scheme. The methodology relies on engineering descriptions of electricity generating

technologies and how their competitive positions vary with a CO₂ price or change in fuel price. Energy efficiency options are represented in the standard CGE format, where non-energy inputs can be substituted for energy inputs within economic production functions or consumer demand equations, as the price of energy increases. The analysis shows that the electric power sector provides substantial opportunities for fuel switching and the deployment of advanced electricity generating technologies, with and without CO₂ capture and storage. Furthermore, it accounts for reduction of emissions of non-CO₂ gases, which adds a set of mitigation opportunities not usually included in energy-economic modeling efforts.

The fourth study (chapter 5) puts a focus on renewable energy and learning. In this chapter, alternative ways of modeling learning-by-doing in the renewable energy sector are analyzed within a top-down multi-region multi-sector CGE model, LEAN_2000. Conventionally, learning-by-doing effects in the renewable energy sector are allocated to the production of renewable based electricity. The study builds on the observation that learning-by-doing also takes place in sectors that deliver capital goods to the renewable electricity sector, in particular in the production of machinery and equipment for renewable energy technologies. Therefore learning-by-doing is implemented alternatively in the renewable energy equipment industry and in renewable electricity production and it is shown why it matters to differentiate between these two approaches. The main differences originate from effects on international trade, since the output of the machinery and equipment sector is intensively traded on international markets unlike renewable electricity. In addition to international trade of a specific good, such as renewable energy equipment, knowledge and technical know-how about this good, which is responsible for learning processes, can spill over from one country to another. Depending on how such spillover effects are treated substantial effects on domestic production and exports patterns can be observed and are analyzed in this chapter.

Although the individual studies are done in collaboration with research partners, I myself am responsible for the main and substantial parts. This relates to methodological research, model implementation, data collection, model runs, interpretation of results, conclusions and write-up. In particular, I set up the German version of the SGM model, implemented the technology set-up for both the electricity and the iron and steel sector, included greenhouse gas mitigation options, conducted the analysis, interpreted the results and wrote and illustrated the papers. For the application in the LEAN_2000 model, I implemented the learning-by-doing approach in the two alternative sectors, collected and adjusted the

appropriate data, conducted the analysis and sensitivity runs, compared, analyzed and illustrated the results, and wrote the paper. Any remaining inaccuracies in this thesis are my responsibility.

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2 Electricity sector innovations in climate policy modeling for Germany⁷

2.1 Introduction

Due to the size and structure of its economy, Germany is one of the largest carbon emitters in the European Union. It is responsible for approximately 800 million tons of carbon dioxide (CO₂) emissions annually, accounting for about one-fourth of European Union (EU) greenhouse gas emissions. Compared to the level in 1990, Germany's CO₂ emissions are now 15% lower. Within the burden sharing agreement under the Kyoto Protocol, Germany is committed to reduce carbon emissions by 21% in 2008-2012 compared to 1990. A long-term national target is to reduce CO₂ emissions by 40% by year 2020 relative to 1990. A substantial portion of greenhouse gas emissions is produced by the electricity system. CO₂ emissions due to fossil fuel combustion for electricity production amount to more than 40% of total CO₂ emissions in Germany.

At the same time, Germany is facing a major renewal and restructuring process. Around one-third of its total electric generating capacity, in the form of fossil fuel based generation, may retire within the next twenty years; another one-sixth of capacity, in the form of nuclear power plants, is scheduled to be phased out. With a projected stable electricity demand, this means that almost fifty percent of German electric power capacity could be replaced within the next twenty years. This provides a substantial window of opportunity for new and innovative technologies such as wind power, coal integrated gasification combined cycle (IGCC), natural gas combined cycle (NGCC), and CO₂ capture and storage (CCS) combined with either coal IGCC or NGCC. Substantial mitigation possibilities in the electricity sector exist in the form of reducing demand through more efficient end-use technologies, or on the generation side through advanced generating technologies or substitution of less carbon-intensive fuels. CCS has received much attention recently as it allows continued use of fossil fuels while emitting much less CO₂ to the atmosphere. CCS has the potential to reduce global emissions up to 50% by 2050 (IEA, 2004). A recent study by the International Energy Agency calls for governments to step up their support for CCS and increase research on these technologies (IEA, 2004).

⁷ This chapter is based on a publication in the Journal of Energy Policy (Schumacher and Sands, 2006).

Various environmental and energy policy efforts are in place to reduce emissions and increase the share of environmentally friendly technologies in Germany. For example, an ecological tax reform was introduced in 1999. A renewable energy law to increase the share of renewable energy, and a combined heat and power (CHP) law to increase the share of CHP based electricity production, were also put into force. More stringent voluntary agreements on reducing industrial carbon emissions were established.

Trading of emissions rights is also a major theme because of its market-based approach and its economically efficient way of meeting emissions targets. The EU decided to implement a European-wide emissions trading program in 2005, while the Kyoto Protocol allows Annex I countries to begin emissions trading in 2008. Additional policies are in place to enhance the share of advanced technologies and to promote efficient transformation and consumption of energy.

It is expected that advanced and innovative generating technologies will play an increasingly important role in electric power production in Germany. These new technologies and their role within a future German electricity generation mix are the focus of this study. Specifically, we ask how climate change policy and fuel price development affect German electricity production and consumption until 2050 given the need to renew substantive parts of German power generation capacity.

We simulate the introduction of advanced electricity technologies in a computable general equilibrium model for Germany, the Second Generation Model (SGM), and analyze the costs of reducing carbon emissions under different policy scenarios. SGM-Germany is a dynamic recursive, multi-sector general equilibrium model based on national input-output data, national energy balances, and country-specific engineering cost information for each electric generating technology. These data are combined in the general equilibrium model to maintain the technological richness of a market-based energy system comprised of conventional and advanced electric generating technologies.

We first develop a baseline simulation of the German economy and energy system from 1995 through 2050 in five-year time steps, including a description of electricity generation by technology. Next, the model is exercised at various carbon prices to estimate the cost of reducing carbon emissions below the baseline. We consider a wide enough range of carbon prices to provide an estimate of the carbon price needed to meet Germany's Kyoto target.

We are also interested in calculating the carbon price at which electric generating technologies, both with and without CCS, become economically competitive. Simulation results are sensitive to engineering cost assumptions on the generating technologies, and we have collected a range of such data from various sources. One important characteristic is the break-even carbon price for introducing CCS, either with IGCC or NGCC technologies. In addition, we consider the role of renewable energy and conduct a similar break-even analysis for wind technologies.

Section 2.2 gives a brief overview of the current structure of the German electricity system. It highlights important features with respect to the electricity generation mix, emissions trends, past and future technologies, and costs. We introduce the SGM model in section 2.3 and describe how it can be used to analyze the costs of carbon mitigation under different policy and technology assumptions. In section 2.4, we discuss results for the electricity sector and then place them in context of the overall economy.

2.2 German electricity sector

Currently, nuclear and fossil fuels dominate electricity production in Germany. More than 50% of electricity is produced from hard coal and lignite, and another 28% from nuclear fuels. Renewable energy sources, so far, account for only a small share (7.4%). Over the last decade, however, production from renewables, in particular wind, has substantially increased (see Figure 2.1). The electricity sector is responsible for more than 40% of German CO₂ emissions (see Figure 2.2).

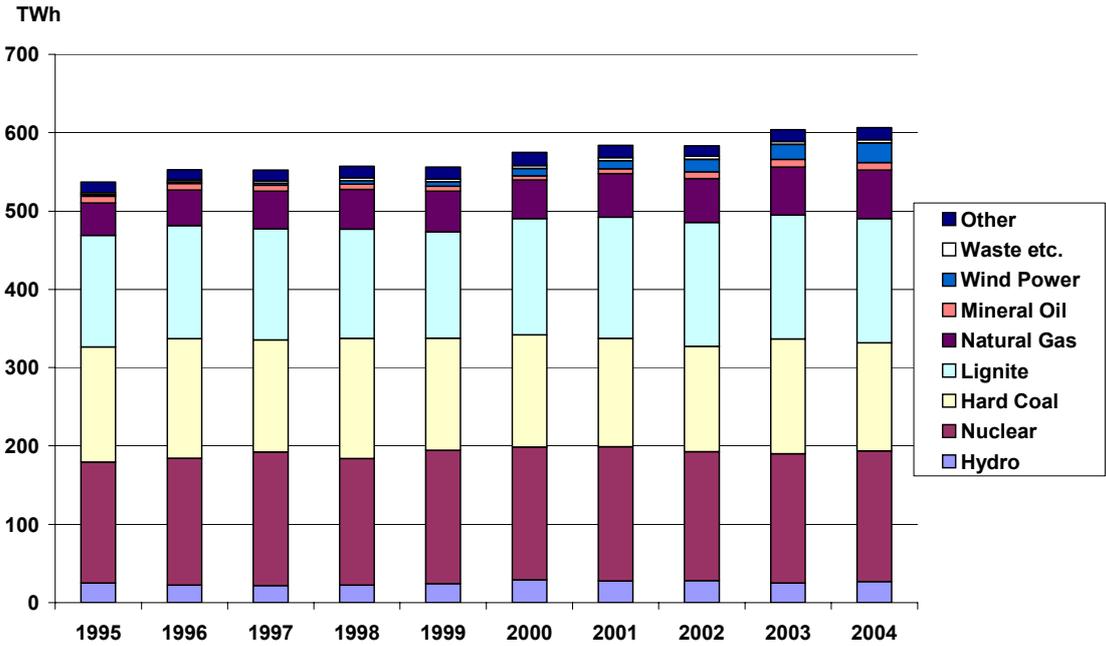


Figure 2.1 Gross electricity production by fuel (in TWh)

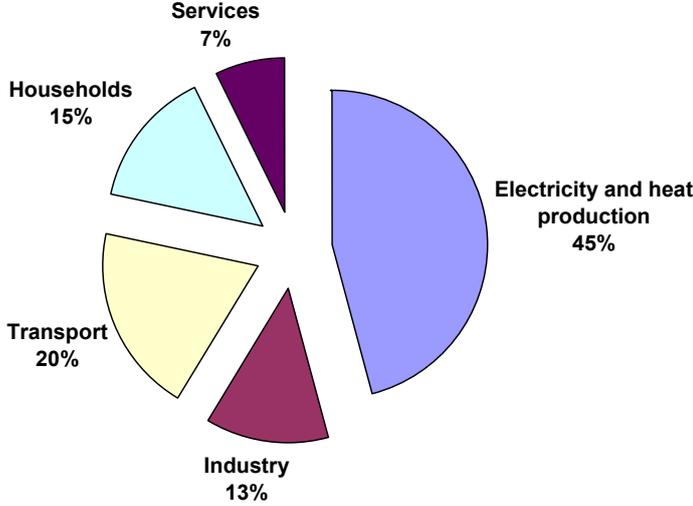


Figure 2.2 CO₂ emissions by sector (% share); Germany 2003

A substantial restructuring of the electricity sector will be needed within the next two decades. About 40 gigawatts (GW) of fossil fuel based power capacity may retire within this period and another 18 GW of nuclear power capacity could go off-line in accordance with the German nuclear phase out pact of 1998. Some combination of new generating plants or

reduced electricity demand (Enquete, 2002) is needed to cover the shortfall in generation. The need for substantial (replacement) investments provides a window of opportunity for new and innovative technologies to play a role in the future electricity mix.

Among these new and innovative technologies are fossil fuel based and renewable energy based technologies. Advanced coal technologies include pulverized coal (PC) with CCS, IGCC, and IGCC with CCS. Advanced natural gas technologies include NGCC and NGCC with CCS. We also consider an advanced offshore wind technology that is expected to be available between 2010 and 2020. The technologies differ substantially in costs and performance. Since our analysis is focused on Germany, we aim at including as much country-specific information as possible.

Table 2.1 Cost and performance measures of new electricity technologies with and without CO₂ capture and storage

| Cost and Performance Measures | Wind | PC Plant | | | IGCC Plant | | | NGCC Plant | | |
|--|------|----------|------------------|-------|------------|------------------|-------|------------|------------------|-------|
| | FIZ | Enquete | David/ Herzog | IEA | Enquete | David/ Herzog | IEA | Enquete | David/ Herzog | IEA |
| Without capture & storage | | | | | | | | | | |
| Conversion efficiency (%) | | 51 | 42 | 43 | 54 | 48 | 46 | 62 | 60 | 56 |
| Emn. rate (kg CO ₂ /kWh) | | 0.629 | 0.756 | 0.746 | 0.594 | 0.671 | 0.697 | 0.294 | 0.301 | 0.323 |
| Investment cost (Euro/kW) | 1908 | 1088 | 1095 | 1075 | 1403 | 1145 | 1455 | 442 | 525 | 400 |
| Capital cost (cent/kWh) | 5.71 | 1.28 | 1.29 | 1.26 | 1.72 | 1.4 | 1.78 | 0.54 | 0.64 | 0.49 |
| Labor cost (cent/kWh) | 1.52 | 0.80 | 0.61 | 0.52 | 1.55 | 0.61 | 0.98 | 0.39 | 0.24 | 0.33 |
| Fuel cost (cent/kWh) | | 1.24 | 1.49 | 1.47 | 1.17 | 1.32 | 1.38 | 2.76 | 2.82 | 3.03 |
| COE (cent/kWh) | 7.23 | 3.32 | 3.39 | 3.26 | 4.44 | 3.34 | 4.14 | 3.69 | 3.7 | 3.84 |
| With capture & storage | | | | | | | | | | |
| Conversion efficiency (%) | | | 36 | 31 | 48 | 43 | 38 | | 55 | 47 |
| Emn. rate (kg CO ₂ /kWh) | | | 0.089 | 0.103 | 0.067 | 0.074 | 0.084 | | 0.033 | 0.038 |
| Investment cost (Euro/kW) | | | 1708 | 1850 | 2033 | 1462 | 2100 | | 850 | 800 |
| Capital cost (cent/kWh) | | | 2.01 | 2.17 | 2.49 | 1.79 | 2.58 | | 1.04 | 0.98 |
| Labor cost (cent/kWh) | | | 1.16 | 1.39 | 2.07 | 0.85 | 1.59 | | 0.42 | 0.55 |
| Fuel cost (cent/kWh) | | | 1.66 | 2.04 | 1.32 | 1.38 | 1.67 | | 3.22 | 3.61 |
| Storage cost (cent/kWh) | | | 0.87 | 1.02 | 0.66 | 0.72 | 0.83 | | 0.32 | 0.38 |
| COE (cent/kWh) | | | 5.70 | 6.62 | 6.54 | 4.75 | 6.66 | | 5.01 | 5.51 |
| Cost penalty (cent/kWh) | | | 2.31 | 3.36 | 2.10 | 1.41 | 2.52 | | 1.31 | 1.67 |
| Difference in emissions (kg CO ₂ /kWh) | | | 0.67 | 0.64 | 0.53 | 0.60 | 0.61 | | 0.27 | 0.28 |
| Cost of CO ₂ avoided (€/t CO ₂) | | | 35 | 52 | 40 | 24 | 41 | | 49 | 59 |

Source: Fachinformationszentrum Karlsruhe (FIZ) (2003); Enquete (2001); David and Herzog (2000); IEA (2004).

Note: Levelized costs are calculated at a 7% interest rate, a projected 2010 gas price of 4.71 €/2000/GJ, and coal price of 1.76 €/2000/GJ. CO₂ capture for pulverized coal plant via chemical absorption. Wind plant is hypothetical off-shore plant (30km distance from the coast).

Table 2.1 provides a summary of cost and performance measures from various studies. In order to compare across sources, we calculate a levelized cost for each technology based on common assumptions with respect to interest rates (7%) and fuel prices (4.71 €/GJ for gas, 1.76 €/GJ for coal). The levelized costs of electricity production (COE) for each technology consist of

$$\text{COE} = \text{capital cost} + \text{labor cost} + \text{fuel cost} + (\text{capture costs} + \text{storage costs})$$

Capture costs include incremental fuel, capital and labor costs for capturing the carbon emissions. We assume that 90% of total carbon emissions can be captured. Transport and storage costs of 11 € per t CO₂ are based on assumptions provided in Enquete (2002).

Interestingly, levelized costs of electricity production do not differ much among the three data sources, with the exception of the David and Herzog assumptions on IGCC generation (with and without CCS) with substantially lower capital and labor costs. The numbers we employ are well in the range of technology characteristics shown in the literature. Rubin et al. (2004) provide a range of these characteristics, indicating the low and high numbers for each technology (see Table 2.2).

Table 2.2 Overview of cost and performance of new fossil technologies with and without carbon dioxide capture and storage

| Cost and Performance Measures | PC Plant | | IGCC Plant | | | NGCC Plant | | | |
|--|--------------|-------|---------------|--------------|-------|---------------|--------------|-------|---------------|
| | Range low | high | Rep. Value | Range low | high | Rep. Value | Range low | high | Rep. Value |
| Without capture and storage | | | | | | | | | |
| Emn. Rate (kg CO ₂ /kWh) | 0.722 | 0.941 | 0.795 | 0.682 | 0.846 | 0.757 | 0.344 | 0.364 | 0.358 |
| Capital cost (\$/kW) | 1100 | 1490 | 1260 | 1170 | 1590 | 1380 | 447 | 690 | 560 |
| COE (cent/kWh) | 3.7 | 5.2 | 4.5 | 4.1 | 5.8 | 4.8 | 2.2 | 3.5 | 3.1 |
| With capture and storage | | | | | | | | | |
| Emn. Rate (kg CO ₂ /MWh) | 0.059 | 0.148 | 0.116 | 0.070 | 0.152 | 0.113 | 0.040 | 0.063 | 0.050 |
| Capital Cost (\$/kW) | 1940 | 2580 | 2210 | 1410 | 2380 | 1880 | 820 | 2020 | 1190 |
| COE (cent/kWh) | 6.4 | 8.7 | 7.7 | 5.4 | 8.1 | 6.5 | 3.2 | 5.8 | 4.6 |
| Cost of CO ₂ avoided (\$/t CO ₂) | 42 | 55 | 47 | 13 | 37 | 26 | 35 | 74 | 47 |
| Cost of CO ₂ captured (\$/t CO ₂) | 29 | 44 | 34 | 11 | 32 | 22 | 28 | 57 | 41 |
| Energy penalty for capture (% MW _{ref}) | 22 | 29 | 27 | 12 | 20 | 16 | 14 | 16 | 15 |
| Changes | | | | | | | | | |
| Percent CO ₂ reduction per kWh (%) | 80 | 93 | 85 | 81 | 91 | 85 | 83 | 88 | 87 |
| Percent increase in Capital Cost (%) | 67 | 87 | 77 | 19 | 66 | 36 | 37 | 190 | 110 |
| Percent increase in COE (%) | 61 | 84 | 73 | 20 | 55 | 35 | 32 | 69 | 48 |

Source: Rubin et al. (2004).

Compared to the current average levelized costs of electricity production (Lise et al., 2006), wind and CCS technologies would not play a major role in a business as usual scenario without further policy incentives for carbon mitigation. We will therefore examine the possible roles played by technologies in a number of alternative climate policy scenarios.

2.3 SGM-Germany

We now present an analysis of electricity generating technologies, and their relative roles over time, in the context of German climate policy. 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 a set of engineering costs for each electric generating technology. This is used to construct a fixed-coefficient production function for each generating technology.

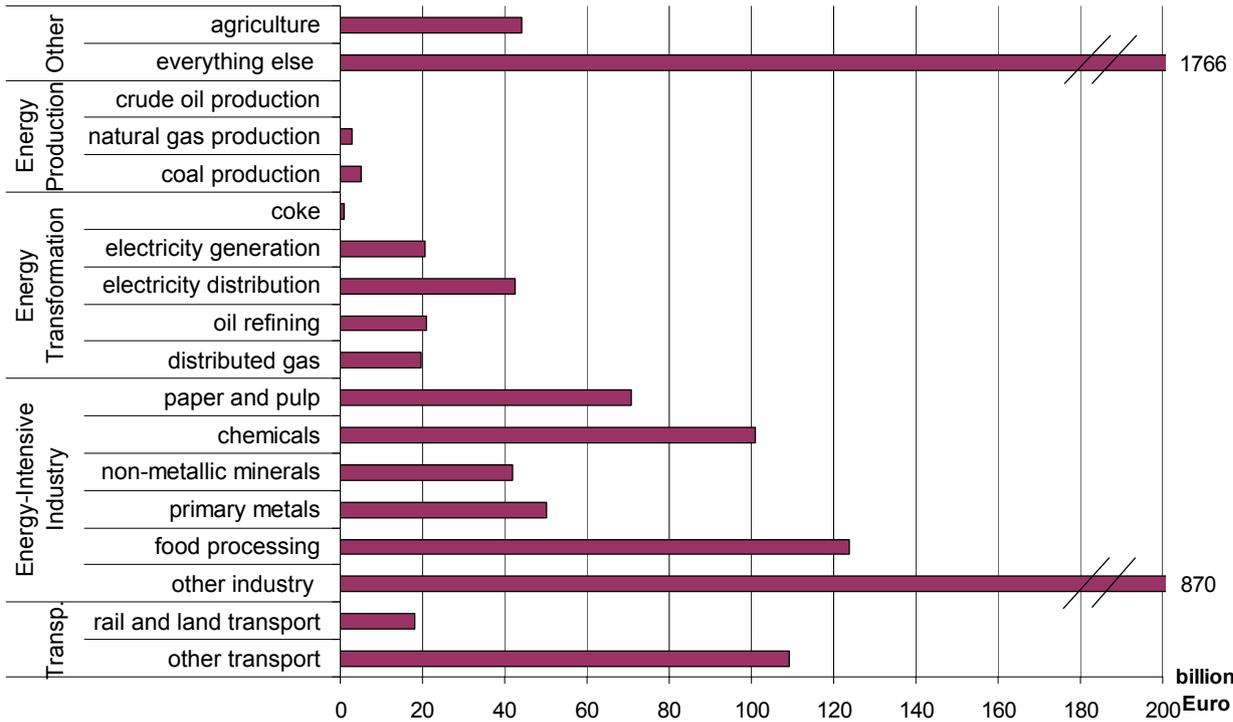


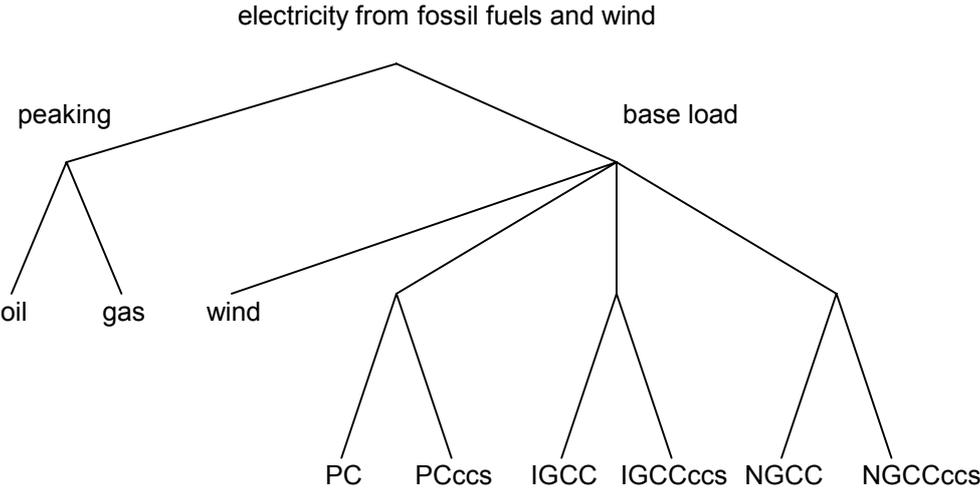
Figure 2.3 Production in SGM-Germany 1995 (billion Euro)

SGM-Germany is constructed with the 18 production sectors shown in Figure 2.3. 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.

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 2.4 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 CO₂. Technologies that are less carbon intensive receive a larger share of new investment than before the carbon price was introduced.



Note: “NGCCcchs” represents NGCC with CO₂ capture and storage, “IGCCcchs” represents coal IGCC with CO₂ capture and storage, “PCcchs” represents pulverized coal with CO₂ capture and storage.

Figure 2.4 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 2.4.

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.

2.4 Analysis and results

As outlined above, a current energy policy focus in Germany is on renewable energy policies and on emission trading. Therefore, our analysis emphasizes those issues, while at the same time accounting for the eco tax and other German-specific features. We introduce two kinds of wind: one is subsidized wind according to the renewable energy law; the other wind category (advanced wind) competes in the open market. Additional baseline assumptions relate to prices of imported fuels, nuclear phase out, minimum use of coal, a constraint in the switchover possibilities to gas for reasons of supply security and to account for inertia of the system. For renewable energy other than wind, we assume hydro capacity is stable over time, as resources are limited, and allow for an increase in biomass and waste based electricity production. The baseline assumptions are in accordance with widely accepted German projections that are outlined in detail in a report for the German government on sustainable energy supply under liberalization and globalization of the energy market (Enquete, 2002). Furthermore, we use the assumptions on costs and performance of new innovative technologies as shown above (section 2.2).

We start out by analyzing levelized cost per kWh as a function of carbon price for advanced technologies: wind, IGCC, PC, NGCC, and CCS. There are two dimensions to the choice of technology. The first is whether or not to use CCS with fossil generating technologies; the second is competition across fuels. We are especially interested in understanding the role wind can play in the future system and at what carbon price it can compete with clean coal technologies. Since wind technology is highly capital intensive (compare Table 2.1), we first conduct sensitivity analyses for the four technologies with respect to the interest rate and fuel prices. This helps us determine the range of carbon prices where pairs of technologies compete directly, or at what carbon price the levelized cost is the same. Pairings of interest include: pulverized coal, NGCC, and IGCC with and without CCS; wind paired with IGCC; and wind paired with IGCC+CCS.

We then use a general equilibrium framework, SGM-Germany, to conduct a baseline analysis and alternative policy scenarios in order to yield information on the future electricity mix, the role of carbon capture and storage technologies within this mix, projections of carbon emissions, and economic growth and costs. Our policy analysis consists of three carbon price scenarios at 10, 25, and 50 € per t of CO₂ starting in 2005. These carbon prices are applied to all sectors of the economy. New fossil technologies (NGCC, IGCC) are introduced to the model beginning in 2015, while technologies with CCS and advanced wind are introduced after 2015.

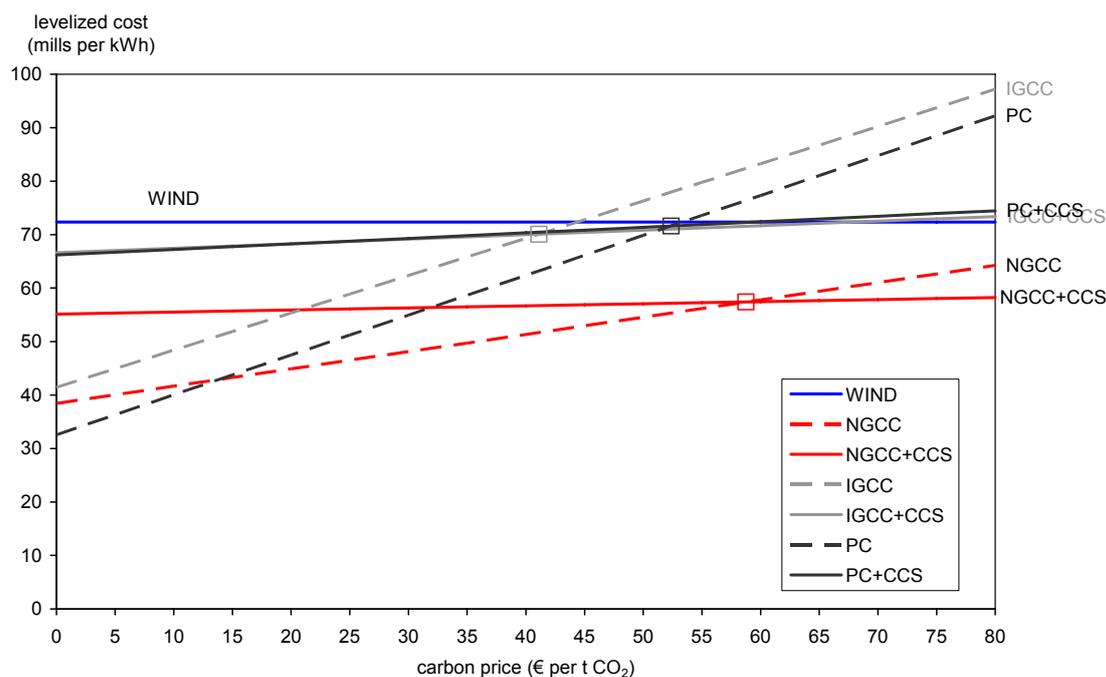
2.4.1 Technology choice

Figure 2.5 provides plots of levelized cost per kWh as a function of carbon price for several electric generating technologies: pulverized coal with and without CCS; IGCC with and without CCS; NGCC with and without CCS; and advanced wind. Competition among these technologies occurs along two dimensions. The first dimension is the decision whether or not to use CO₂ capture. For fossil generating technologies, CCS imposes a greater capital cost, which is offset as the carbon price increases. A break-even, or crossover, carbon price exists for each fossil technology, where the levelized cost is the same with or without CCS. All of the plotted lines in Figure 2.5 are conditional on the interest rate and fuel prices. We use an interest rate of 7%, a gas price of 4.71 €/GJ, and a coal price of 1.76 €/GJ. Fuel prices are taken from Enquete (2001) projections for year 2010.

The second dimension of competition is across fuels, which is influenced by the relative prices of these fuels and the interest rate. The levelized cost per kWh of NGCC technologies

is lower than IGCC technologies at all but the very low values of the carbon price in Figure 2.5. The pattern could reverse with higher natural gas prices because variable costs are already significantly higher for NGCC than for IGCC technologies. Wind is highly sensitive to the interest rate because its main cost component is capital costs. The cost disadvantage of wind may be offset as the carbon price increases, fuel prices increase or interest rates decrease.

At these fuel prices and technology cost assumptions, the crossover price for CCS with IGCC is 41.1 € per t CO₂, while the crossover price for CCS with NGCC is 58.8 € per t CO₂. The crossover price for each technology includes a constant 11 € per ton of CO₂ transport and storage cost. The CCS crossover price is lower for IGCC than for NGCC because the capture process used for coal gasification technologies costs less to employ than the one for natural gas based production. Advanced wind and coal IGCC+CCS have the same levelized cost per kWh at 68 € per t CO₂. This crossover price, however, is very sensitive to technology cost assumptions because both of the corresponding lines in Figure 2.5 have a very low slope.



Notes: “NGCC+CCS” represents NGCC with CO₂ capture and storage, “IGCC+CCS” represents coal IGCC with CO₂ capture and storage, “PC+CCS” represents pulverized coal with CO₂ capture and storage. Crossover prices where CCS breaks even are marked with a square for each fossil generating technology. Based on: IEA, 2004; Fachinformationszentrum Karlsruhe, 2003.

Figure 2.5 Levelized cost as a function of carbon price

Figure 2.6 shows the sensitivity of the break-even carbon prices for CCS with IGCC, pulverized coal, and NGCC technologies to the interest rate. The lines show the combination of carbon prices and interest rates that would allow the CO₂ capture and storage technologies

and their regular counterparts to break even in terms of levelized costs. The break-even carbon prices increase somewhat with the interest rate, indicating that capture and storage processes are capital intensive.

Figure 2.6 also shows carbon price and interest rate combinations where IGCC+CCS and advanced wind have the same levelized cost. This relationship is of interest in Germany, where both wind and coal are major domestic resources and could play an important role in the development and restructuring of the electricity system. The crossover price of wind vs. IGCC+CCS is highly sensitive to changes in the interest rate. If the capital cost for advanced wind is increased to account for backup generating capacity, then the crossover carbon price would be even more sensitive to changes in capital markets. The lines for the fossil technologies are less steep, indicating a lower sensitivity to changes in interest rates. Lower interest rates provide an advantage for wind because wind is more capital intensive than IGCC+CCS.

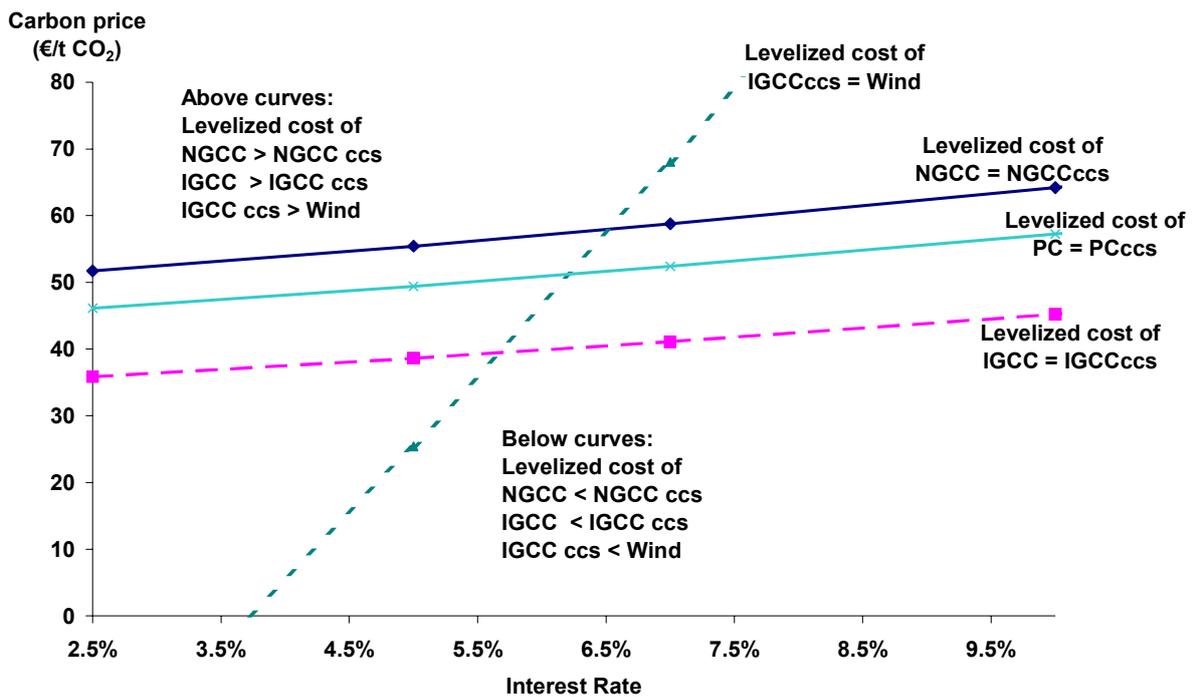


Figure 2.6 Sensitivity of crossover price with respect to interest rate

Figure 2.7 shows a similar sensitivity analysis, but now with respect to fuel prices. We increase prices for coal and natural gas by the same percentage and calculate the carbon price where levelized costs are equal between technology pairings of interest. CCS technologies are more fuel intensive than their counterparts, and the break-even carbon prices increase somewhat with respect to fuel prices. We see again that advanced wind vs. IGCC+CCS shows

a high sensitivity to cost assumptions, including fuel costs. High fuel prices can offset the capital cost disadvantage of wind power.

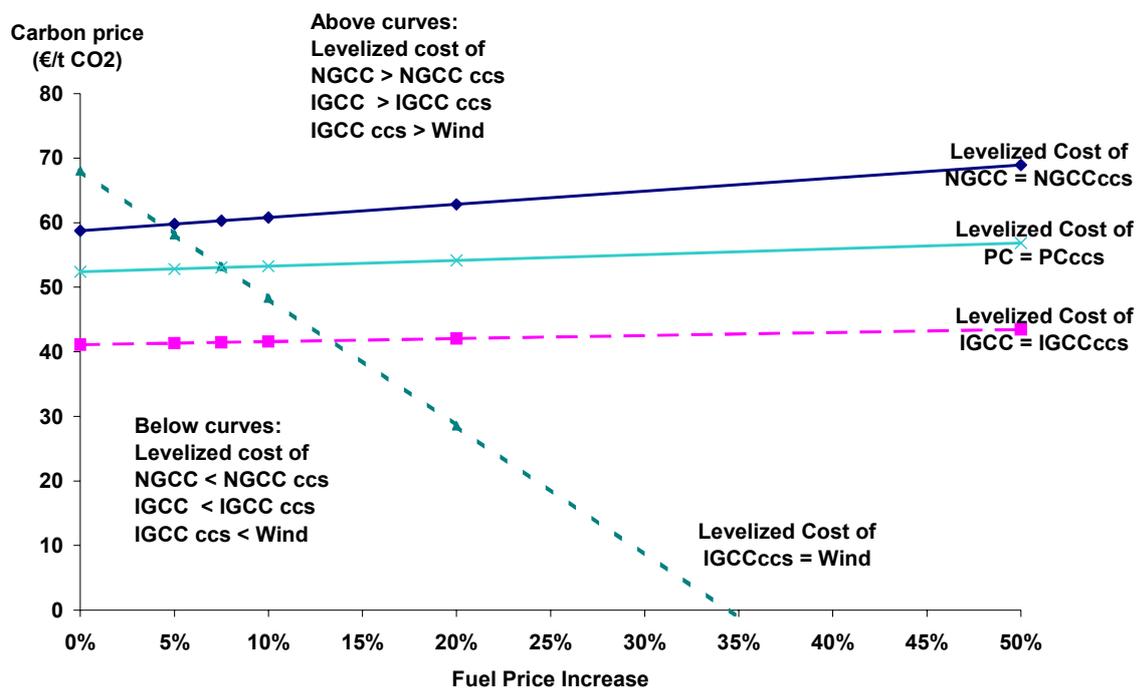


Figure 2.7 Sensitivity of crossover price with respect to fuel price increase (at fixed 7% interest rate and starting with 2010 fuel prices)

Sensitivity analyses in Figure 2.6 and Figure 2.7 reveal that break-even prices for CCS technologies are relatively robust with respect to interest rates and fuel prices, remaining in a price range of 35 to 55 € per t CO₂ for CCS with pulverized coal or IGCC. The ability of wind to compete with IGCC+CCS, however, is much more sensitive to interest rates and fuel prices.

2.4.2 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 carbon price assumptions.

Figure 2.8 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.

CO₂ 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 old capital retires. Outside the electricity sector, SGM-Germany uses a capital lifetime of 20 years.

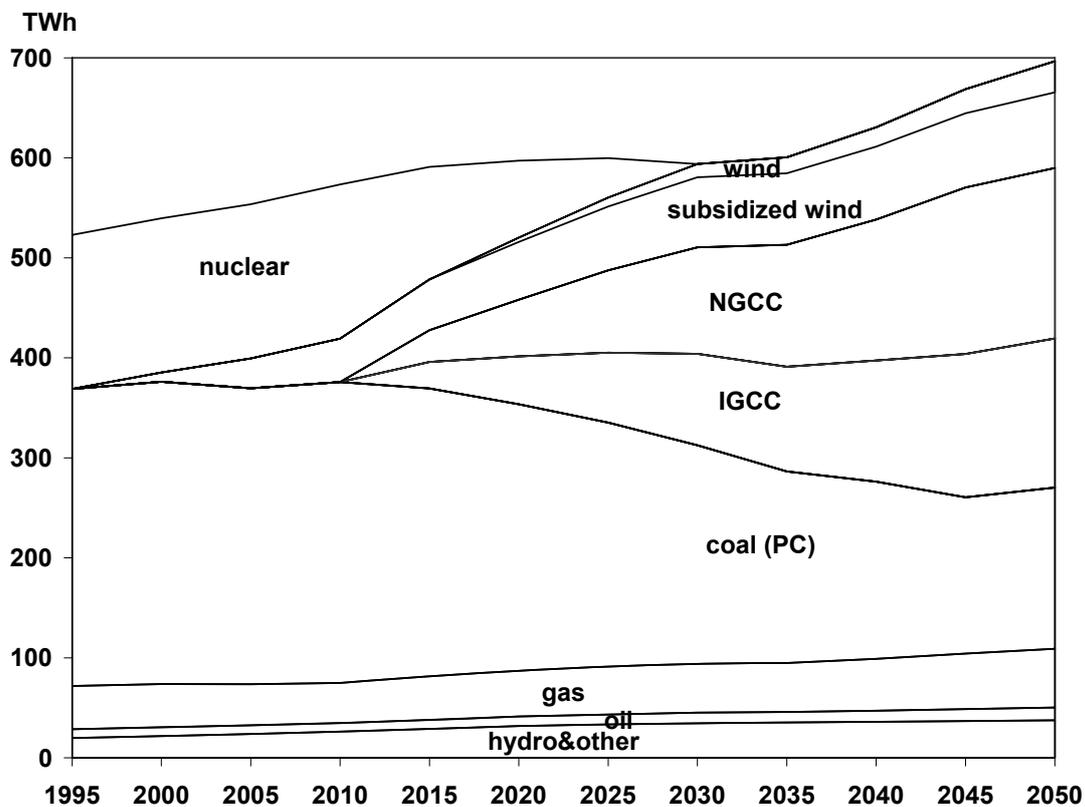


Figure 2.8 Baseline electricity generation in TWh

Figure 2.9 shows results with a carbon price of 50 € per t CO₂ introduced in year 2005 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 crossover price for CCS with IGCC, so a large share of IGCC capacity includes CCS by 2050. A carbon price of 50 € per t CO₂ is below the crossover 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 € per t CO₂), CO₂ capture and storage technologies as well as advanced wind still come into place, but with a reduced share of generation.

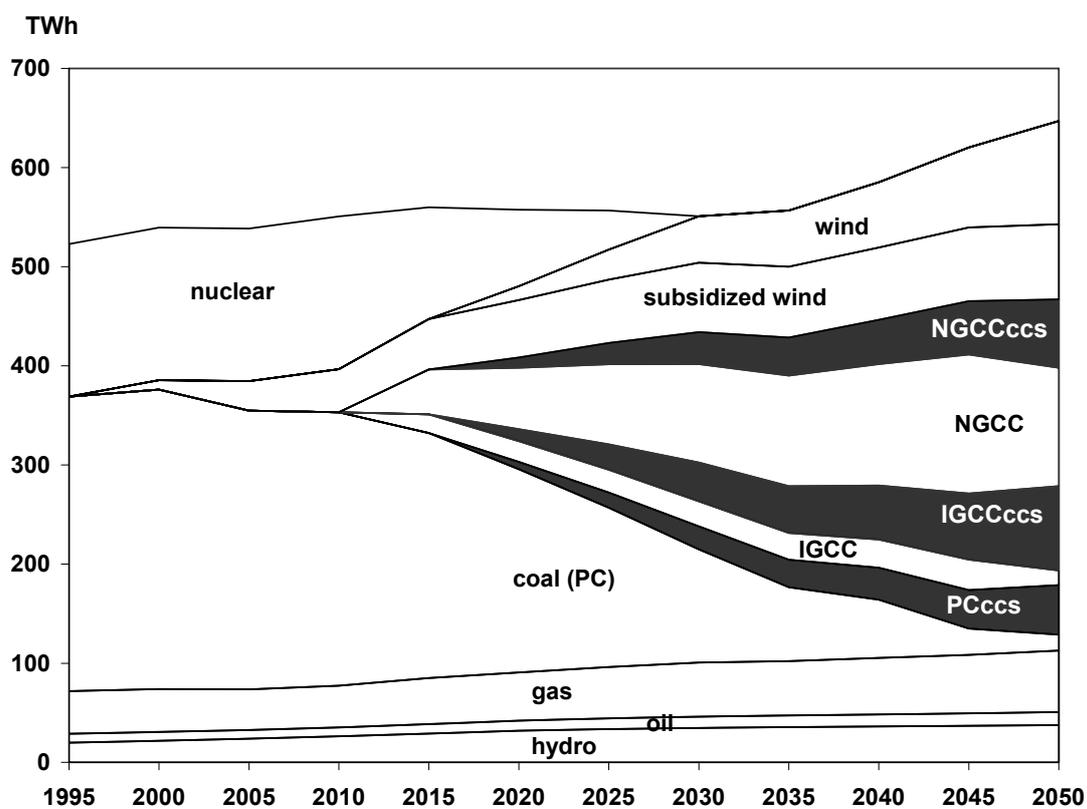


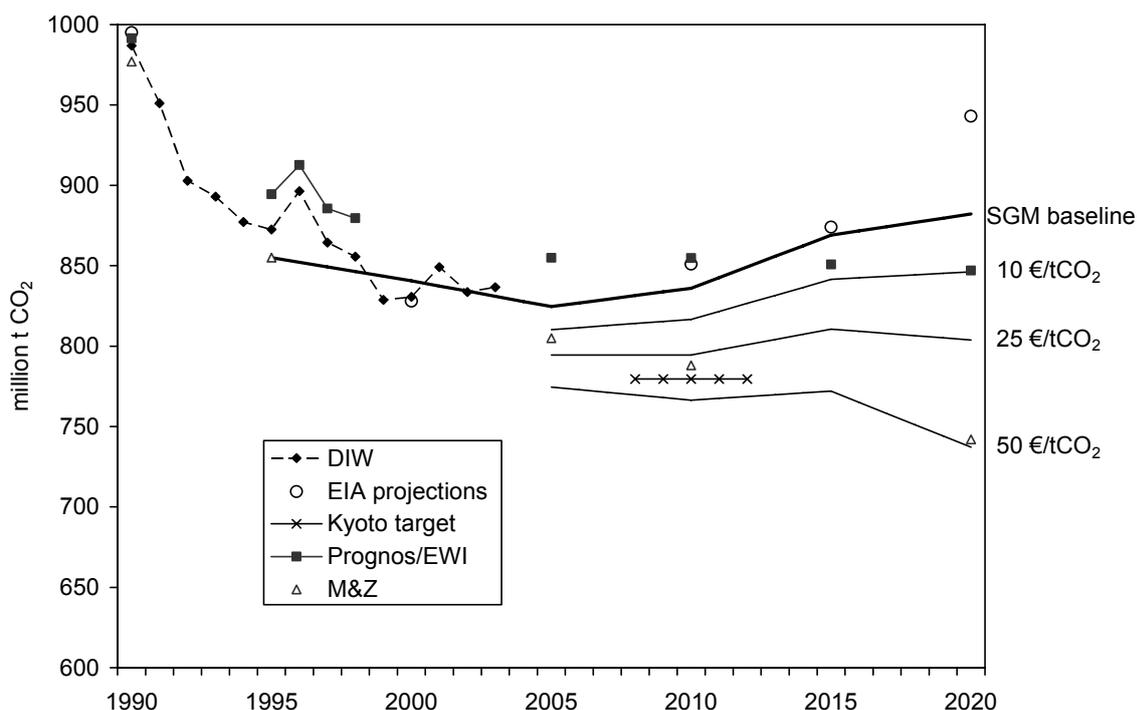
Figure 2.9 Electricity generation mix with carbon price 50 € per t CO₂

2.4.3 Economic and emissions results

Figure 2.10 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 2.10 are baseline scenarios to the year 2020. Also included are projections of carbon emissions at carbon prices of 10, 25, 50 € per t CO₂. All of these scenarios are shown relative to historical carbon emissions (DIW, 2004) and Germany's

Kyoto emissions target. The figure also includes projections of carbon emissions from Markewitz and Ziesing (M&Z 2004), Prognos/EWI (1999) and the U.S. Energy Information Administration (2002).

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 € per t CO₂ reduces emissions by 2.3% compared to baseline emissions of 836 Mt CO₂ in 2010; a price of 25 € per t CO₂ reduces emissions by 5% and a 50 € per t CO₂ price by 8.3%. If the Kyoto target of reducing CO₂ emissions by 21% to 780 Mt CO₂ was solely to be met by adding a price on carbon dioxide, the price would be approximately 35 to 40 € per t CO₂. This estimate of a carbon price needed to meet the Kyoto clearly depends on the baseline emissions scenario. If baseline emissions continue to decline after 2005, then a lower carbon price is needed.

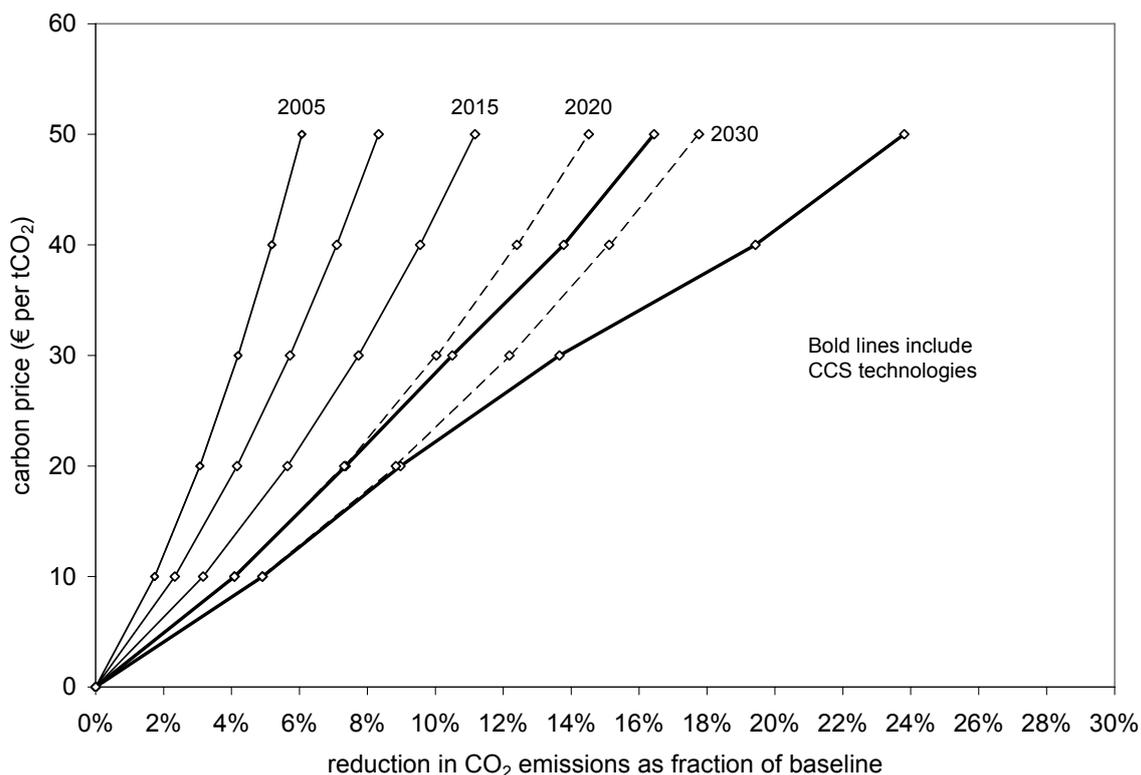


Note: Advanced electric generating technologies in these scenarios include integrated gasification combined cycle (IGCC), natural gas combined cycle (NGCC), and wind. CO₂ capture and storage is introduced after 2010 in new generating plants.

Figure 2.10 Projections of carbon dioxide emissions in Germany (Mt CO₂)

The importance of CCS technologies in reducing CO₂ emissions is depicted in Figure 2.11. The marginal abatement cost curves show the level of carbon price needed to achieve a specific emissions reduction target compared to the baseline. A marginal abatement cost curve

is plotted for each target year. Since CCS technologies are introduced after 2015, the marginal abatement cost curves with CCS differ from the others. With CCS, a lower carbon price is needed for any given emissions target after 2015. Another way to state this is that greater emissions reductions can be obtained for the same price of CO₂ when including CO₂ capture and storage technologies. The gap between marginal abatement cost curves becomes more pronounced the higher the carbon price.



Note: Carbon dioxide capture and storage is introduced after 2015 in new generating plants.

Figure 2.11 Marginal abatement cost curves with and without CO₂ capture and storage (CCS)

Figure 2.12 provides a description of the source of emissions reductions in the 50 € per t CO₂ scenario. At this price, the deviation from baseline increases over time as old capital is retired. The household sector is an exception, as the SGM household sector does not contain capital stocks. Therefore, the household sector responds more quickly to a carbon price than other sectors.

In 2005, households contribute the largest share of emissions reductions followed by slightly lower and almost equal shares of the electricity sector and other (non-energy-intensive) industries. The picture changes over time and with higher carbon prices as new and

advanced electricity generating technologies come into place. A carbon price of 50 € per t CO₂ induces the electricity sector to install wind and CO₂ capture and storage technologies so that substantial emissions reductions can be achieved. By 2020, the electricity sector accounts for emissions reductions of 68 Mt CO₂, which is slightly less than 50% of the total 145 Mt CO₂ emissions reductions achieved in this policy scenario (see Figure 2.12).

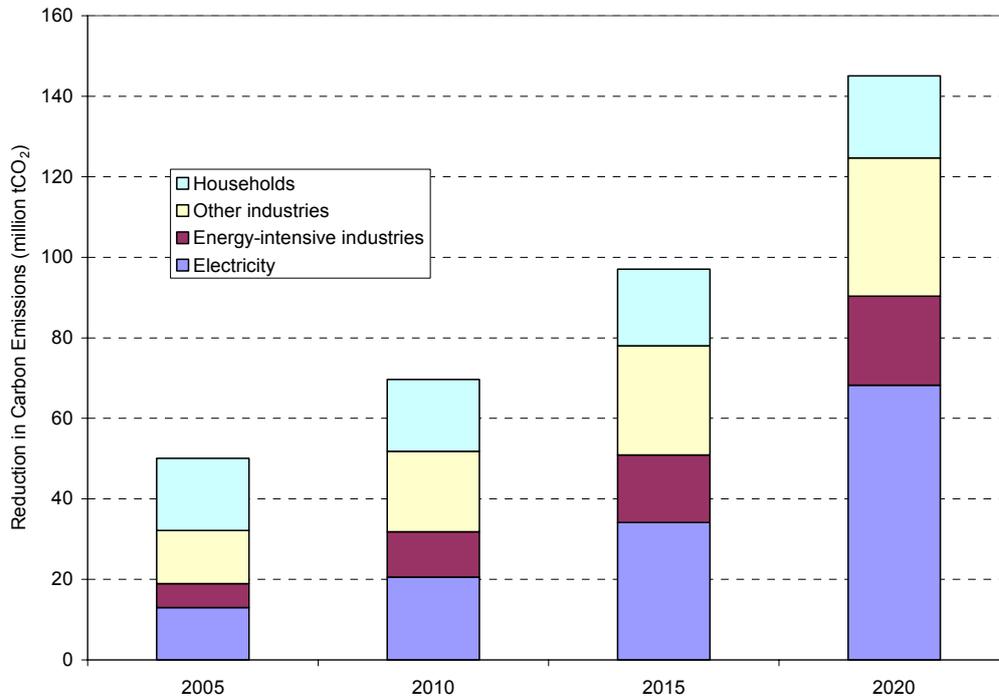


Figure 2.12 Decomposition of emissions reductions with a carbon price of 50 € per t CO₂

Figure 2.13 shows how quantity of gross output varies by sector aggregate in the 50 € per t CO₂ 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%. 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. Energy transformation sectors have the largest percentage reduction in output, while the reduction in output across energy-intensive industries is less than 2.0%.

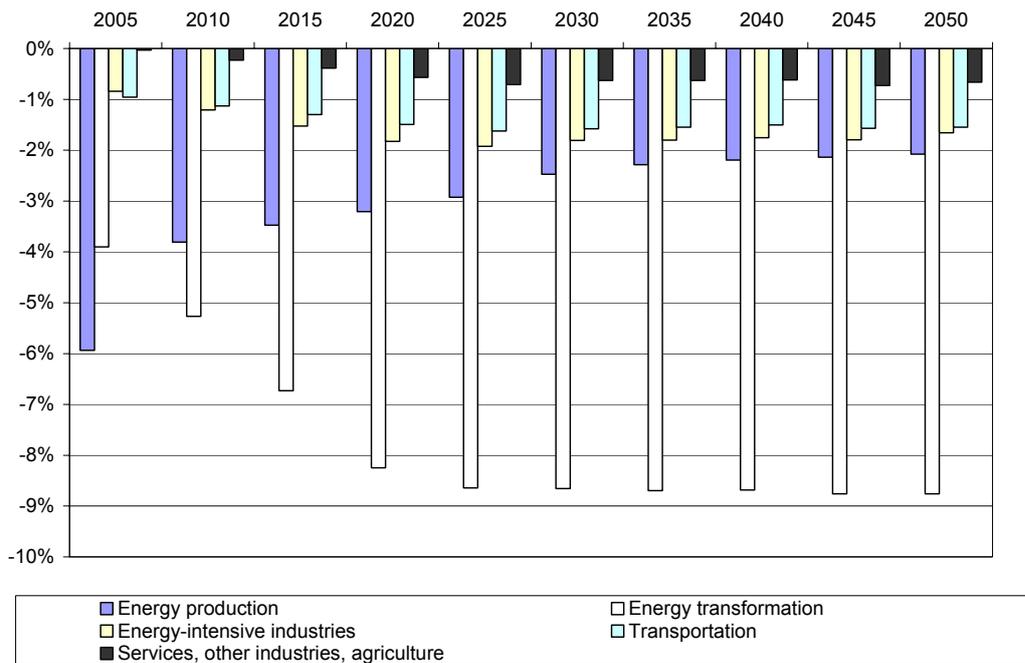


Figure 2.13 Change in sectoral output, 50 € per t CO₂ case compared to baseline

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% to 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.

These carbon policy simulations apply a common carbon price to the entire economy, and revenues from the carbon policy are recycled as a lump sum to consumers. Losses in real GDP in connection with this efficient carbon mitigation scenario are less than 0.7% of GDP in 2050 even for a carbon price as high as 50 € per t CO₂. For a carbon price of 25 € per t CO₂, the GDP loss is 0.3% in 2050 compared to the baseline.

2.5 Summary and conclusions

We have two primary objectives in this study. The first is to construct an advanced methodology for analysis of energy and climate policy that links the German economy with new electricity generating technologies. The second is to provide plausible scenarios of electricity generation in Germany over the next several decades, considering the anticipated phase-out of nuclear generation and the introduction of advanced generating technologies, with and without a climate policy.

Our methodology relies on engineering descriptions of electricity generating technologies and how their competitive position varies with a carbon price or change in fuel price. Although much analysis can be conducted by comparing levelized cost across technologies as a function of the carbon price and fuel prices, we place these technologies in a computable general equilibrium model of Germany. What is gained by doing this analysis within a CGE model? First, the demand for electricity is determined endogenously within the model: a carbon policy increases the cost of electricity to consumers and this is reflected in reduced demand. Second, it provides a comparison of greenhouse gas mitigation opportunities between the electric power sector and the rest of the economy. Third, estimates of the cost of a carbon policy can be constructed, which are sensitive to pre-existing energy taxes. We have therefore constructed a flexible tool for simulating carbon dioxide emissions that can accommodate a wide variety of assumptions about electricity technologies, carbon prices, fuel prices, and baseline energy consumption.

The carbon price required to meet an emissions target, such as in the Kyoto Protocol, depends on baseline energy consumption, the rate that capital stocks turn over, and the set of available generating technologies. The importance of CCS technologies becomes evident when looking at marginal abatement cost curves with and without CCS. An emissions reductions target can be achieved at equal or lower marginal costs when CCS technologies are included. In particular, marginal abatement costs are substantially lower in the long run with new advanced electricity generating technologies in place.

It is useful to think of technology pairings, and the carbon prices that induce switching between technologies. Technology pairings of interest include IGCC with and without CCS, pulverized coal with and without CCS, and NGCC with and without CCS. Of these, IGCC+CCS has the lowest break-even carbon price (about 41 € per t CO₂) while NGCC+CCS has the highest (59 € per t CO₂). Another pairing of interest is wind power relative to IGCC or IGCC+CCS. All of the key carbon prices vary along with fuel prices, interest rates, and technology costs. The variation is most pronounced for wind power, which is highly capital intensive and thus responsive to interest rate changes. The competitiveness of advanced wind power with the IGCC+CCS technology advances substantially as interest rates fall, fuel prices rise, or carbon prices increase. With a carbon policy, advanced technologies replace at least part of electricity generation lost from a phase-out of nuclear generation or due to plant retirement. We conclude that a carbon price range of 35 to 55 € per t CO₂ is a critical range for CCS as well as advanced wind technologies to play a major role.

If the Kyoto reduction target of 21% for Germany were to be reached by means of a carbon price alone (no additional policies), our simulation requires a carbon price of 35 to 40 € per t CO₂ to meet that target. A more stringent target, such as the goal of 40% fewer emissions relative to 1990, would require even higher carbon prices. These estimates would change if baseline emissions turn out to be different from our projections, but even the Kyoto target, if kept as Kyoto-forever target, may be stringent enough to consider advanced wind and CCS as mitigation options.

In this study, we have simulated an economy-wide carbon policy in Germany, where all consumers and producers face the same carbon price. A possible extension would be to consider sector-specific policies with some sectors exempt from the carbon price. This would allow an estimate of the loss in economic efficiency for policies, such as in the European Union, that target specific production sectors such as electricity generation and energy-intensive industries. Another interesting extension would be to consider alternative scenarios of electricity trade between Germany and neighboring countries.

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3 An innovative CGE approach for the inclusion of industrial technologies in energy-economy models⁸

3.1 Introduction

Industrial technologies, their energy consumption and change over time, are important for analysis of energy and climate policies. Bottom-up models simulate the operation of specific energy technologies based on cost and performance characteristics in a partial equilibrium framework. They contain detail on current and future technological options but lack interaction with the rest of the economy. Top-down models, including computable general equilibrium (CGE) models, use a broader economic framework. However, in order to include behavioral and other non-technical factors such as policy instruments, they usually compromise on the level of technology detail, which may be relevant for an appropriate assessment of energy or climate policies (Jaffe et al., 2003; Edmonds et al., 2001).

Energy-intensive industries are commonly represented in general equilibrium models as abstract economic production functions of the constant-elasticity-of-substitution (CES) or translog functional form. This study demonstrates an alternative approach based on cost and performance data for specific iron and steel technologies within a CGE model of Germany. For a more realistic representation of an energy-intensive industry, we replace a CES cost function with a set of fixed-coefficient cost functions describing specific technologies. The technology-specific cost functions are based on engineering cost and performance characteristics.

The focus of this analysis is the representation of industrial energy technologies in a computable general equilibrium framework and we directly address the following questions: What difference does it make in a CGE model whether the iron and steel sector is represented by an aggregate production function or by distinct steel-producing technologies? How might a climate policy affect the iron and steel sector in the context of overall economic activity?

CGE models are used extensively for analysis of energy and climate policy and offer several advantages. They emphasize the interaction between energy and non-energy markets and simulate combined, economy-wide, responses to price changes induced by such policies.

⁸ This chapter is based on a paper accepted for publication in the *Journal of Energy Economics* (Schumacher and Sands, 2007).

Employing a general equilibrium framework allows for sectoral output adjustments in response to higher production costs, which may be induced by climate policies. It allows us to analyze interactions between production sectors, for example between electricity generation and iron and steel production, and to investigate a combined response to changes in relative prices. The carbon intensity of electricity and iron and steel can change simultaneously. Handling both sectors within a common framework avoids double counting of emissions reductions. The CGE approach helps determine where in the economy and energy system reductions in greenhouse gas emissions are more likely to occur.

However, the aggregate production functions typically used in CGE models are only abstract representations of energy-intensive industries, each of which contains a complex set of production routes. The aggregate production functions are consistent with base-year energy consumption across technologies within an industry because they are calibrated to base-year economic and energy data. However, it may not be possible to demonstrate that simulated changes in energy consumption, in response to changes in prices or other economic drivers, are consistent with shifts among technologies. This is particularly important for analysis of climate policy where energy prices can be driven far outside their historical range.

Other researchers have addressed the inconsistency of top-down economic analysis with bottom-up engineering approaches to industrial energy use. Böhringer (1998) and Böhringer and Löschel (2006) demonstrate a hybrid approach within a CGE model where electricity generation is represented by bottom-up activity analysis and other sectors are represented by CES functional forms. Another hybrid approach is demonstrated in the CIMS model, which iterates between energy demand, energy supply, and macroeconomic modules (Bataille et al., 2006; Jaccard et al., 2003). Pant (2002) and Pant and Fisher (2004) adopt a technology bundle approach for two production sectors to incorporate technology detail in a dynamic multisector CGE model. Li et al. (2003, 2000) use a similar approach for known electricity technologies in the case of Taiwan. Recent efforts devoted to coupling detailed energy models, such as MARKAL, with CGE frameworks include those by Schäfer and Jacoby (2006, 2005) for transport technologies and by Proost and van Regemorter (2000) for energy services in the Belgium economy.

We select the iron and steel sector because it is one of the most energy-intensive sectors in the majority of industrialized countries, and is responsible for a large share of greenhouse gas emissions. The industry is subject to climate and energy policies to improve energy efficiency, induce innovation, and reduce greenhouse gas emissions, which may put the

international competitiveness of the industry at stake (Ameling and Aichinger, 2001; Rynkiewicz, 2005). Currently, two main technology alternatives exist in this sector: the oxygen or integrated technology where iron ore is smelted by burning fossil fuels, and the electric arc furnace which melts scrap steel using electricity. While the integrated technology is mainly based on coke, coal, and iron ore feedstocks, the electric arc furnace is highly electricity intensive and based mainly on scrap input. New and innovative technologies are expected to play a major role in the near future (Daniels, 2002; de Beer et al., 1998).

A few studies focus directly on iron and steel production. Lutz et al. (2005) simulate technology choice in German steel production within an econometric multi-sector model. Ruth and Amato (2002) provide a similar study for the United States. Hidalgo et al. (2005) use a global partial equilibrium model of iron and steel to simulate the evolution of the iron and steel industry under a series of emissions trading scenarios. Similarly, Gielen and Moriguchi (2002a, 2002b) apply a partial foresight model (STEAP) of the European Union and Japan to analyze the effect of CO₂ taxes on the iron and steel industry, including trade and leakage effects of unilateral tax settings. Mathiesen and Moestad (2004) use a global static partial equilibrium model (SIM) to investigate the effect of a CO₂ tax in industrialized countries on global steel-related emissions and potential relocation of steel production. However, none of these iron and steel studies provide a direct application to a computable general equilibrium model.

The primary strength of our technology-based approach is that it maintains the richness of engineering characteristics of key technologies, yet allows for a full general equilibrium analysis of energy or climate policies. We work at an intermediate level of technology detail, between the traditional aggregate production functions of top-down models and the extensive technology detail used in bottom-up models. We permit a choice between several technologies for producing steel and allow for shifts in technology characteristics over time towards best practice, innovative technologies. Shifts in energy consumption, in response to changes in energy or CO₂ prices, are consistent with shifts between technologies. This is important for both baseline and policy scenarios. Allowing for shifts in discrete technologies provides flexibility for future technology development to be decoupled from the base year structure. Further, improvements in technology characteristics can be based directly on engineering knowledge and projections.

Although the technology-based approach is a step forward in representing industrial technologies in CGE models, several weaknesses remain. First, even though the level of detail

is much greater than typically found in a CGE model, it is less than in some bottom-up linear programming models. We must make judgments as to the amount of detail to maintain and where to draw a system boundary around the processes we model. In our analysis of iron and steel production, this affects the number of production technologies and the variety of products. For example, we focus on crude steel production technologies, but do not attempt to distinguish downstream processing technologies and types of final steel products. In principle, however, CGE models are well suited to handle further disaggregation of technologies and products, given sufficient data. Second, it remains difficult to find empirical support for the behavioral parameters that determine that rate of shift between technologies as their relative costs change. It is also difficult to parameterize future advanced technologies. Other CGE and linear programming modelers must also determine important behavioral and technical change parameters. This challenge is inherent to all technology modeling and remains a challenge in our technology-based approach. These parameters deserve further, and Germany-specific, empirical justification. Third, even though we have added technology detail to the CGE framework, we still must characterize each steel production route with a single equipment lifetime. This means we have little capability to represent retrofit options and possibilities for lifetime extension. Fourth, this study covers only one of the energy-intensive industries (iron and steel) besides electricity production. An analysis of the effects of climate policy in Germany would deserve technological detail for additional sectors, at least the set of major energy-intensive industries.

Both the aggregate production function approach and the technology-based approach allow for exogenous improvements in energy efficiency within the steel production sector. The ultimate impact of these energy efficiency improvements depends a great deal on substitution elasticities in production processes that use steel. The aggregate production function approach assumes a constant elasticity of substitution among all input factors and exogenous technical change (efficiency) for each input. The technology-based approach assumes fixed input coefficients for each of the technologies; technical change occurs through shifts from one technology to another. These assumptions have implications for the ability of the model to respond to changes of specific prices or factor efficiencies induced, for example, by price or non-price based climate policies (UK Energy Research Centre 2006, Saunders 2000a). We have not explored more general functional forms, such as translog, generalized Leontief or nested CES production functions, or endogenous forms of technical change.

This study is organized as follows. We describe our methodology in section 3.2, including data requirements, two approaches for simulating iron and steel within a general equilibrium framework, and assumptions about technical change over time. Section 3.3 provides background on the iron and steel industry in Germany. It highlights important features with respect to past and future technologies, energy consumption, carbon dioxide emissions, and costs. In section 3.4, we compare the results from the aggregate production function and technology-based approaches, provide detailed results for production and energy consumption for iron and steel technologies, and place these results in the context of overall economic development. Section 3.5 concludes the study.

3.2 Methods

We use the Second Generation Model (SGM; Edmonds et al., 2004), an economy-wide computable general equilibrium model, to demonstrate two approaches for modeling steel production in Germany.⁹ A common approach for CGE models is to simulate iron and steel production using a CES functional form that does not differentiate among specific technologies to produce iron and steel. We refer to this approach as the aggregate production function approach or aggregate CES approach. Our technology-based approach replaces the CES cost function for iron and steel with a logit nest of fixed-coefficient cost functions: each fixed-coefficient cost function represents a specific technology for producing steel with technical coefficients constructed from engineering data. The technology-based approach (or logit nesting approach) has been demonstrated for electricity generation in SGM in Sands (2004) and Schumacher and Sands (2006). This study represents the first application of the logit nesting approach to iron and steel in SGM. Another example of the logit mechanism is in the CIMS model, which uses the same functional form (Jaccard et al., 2003) to determine market share of technologies in new investment.

We are interested in how the aggregate CES and technology-based approaches compare, especially in response to changes in fuel prices or CO₂ prices. We construct several illustrative climate policy scenarios to demonstrate the price response of both approaches. The technology-based approach is data intensive and requires reconciliation of data across

⁹ We use a transitional version of SGM, which includes some features beyond those documented in Fawcett and Sands (2005), and Sands and Fawcett (2005). The major changes are: (1) consumer demand is based on the Linear Expenditure System; (2) sector-level investment is determined by the zero-profit condition that price received equals levelized cost; and (3) the lifetime of capital stocks can be set to any desired multiple of five years.

economic input-output tables, energy balances, and engineering data by technology. However, once a benchmark data set is constructed for the technology-based approach, it can also be used for the aggregate CES approach.

3.2.1 Benchmark data

A benchmark table for the model base year is constructed using a 1995 economic input-output table for Germany (Statistisches Bundesamt, 1995), a 1995 energy balance table for Germany (AGEB, 1999), and cost data for iron and steel technologies (see section 3.3.2). We have some flexibility in how we define production sectors in a CGE model: we maintain detail in production sectors of interest and collapse detail elsewhere. Here we are interested in the behavior of iron and steel technologies, and we use all of the sector detail available for iron and steel from the 1995 input-output table.

Data are organized into a benchmark use table as shown in Figure 3.1. A use table is essentially an expanded input-output table that allows for more production processes than commodities. The intermediate flows section of the table has the same number of rows as distinct products, but in the cases of electricity and steel, several technologies are available for production. The following technologies are available for making steel: basic oxygen furnace (BOF), electric arc furnace (EAF), and a direct reduction process (DRP). Advanced versions of the basic oxygen furnace (BOFA) and the electric arc furnace (EAFA) become available some time after the base year, with a start date determined by the model user.

We distinguish between “crude steel” and “shaped steel” in the benchmark data set, even though the 1995 input-output table for Germany has these activities combined into one sector. We are able to make this distinction using engineering data for the various steel making processes. The processes are quite different up to the point of crude steel (molten steel), but similar afterwards. All output from the crude steel sector becomes an input to the steel shaping sector. All other sectors consume steel as shaped steel. These relationships are shown as shaded areas in Figure 3.1.

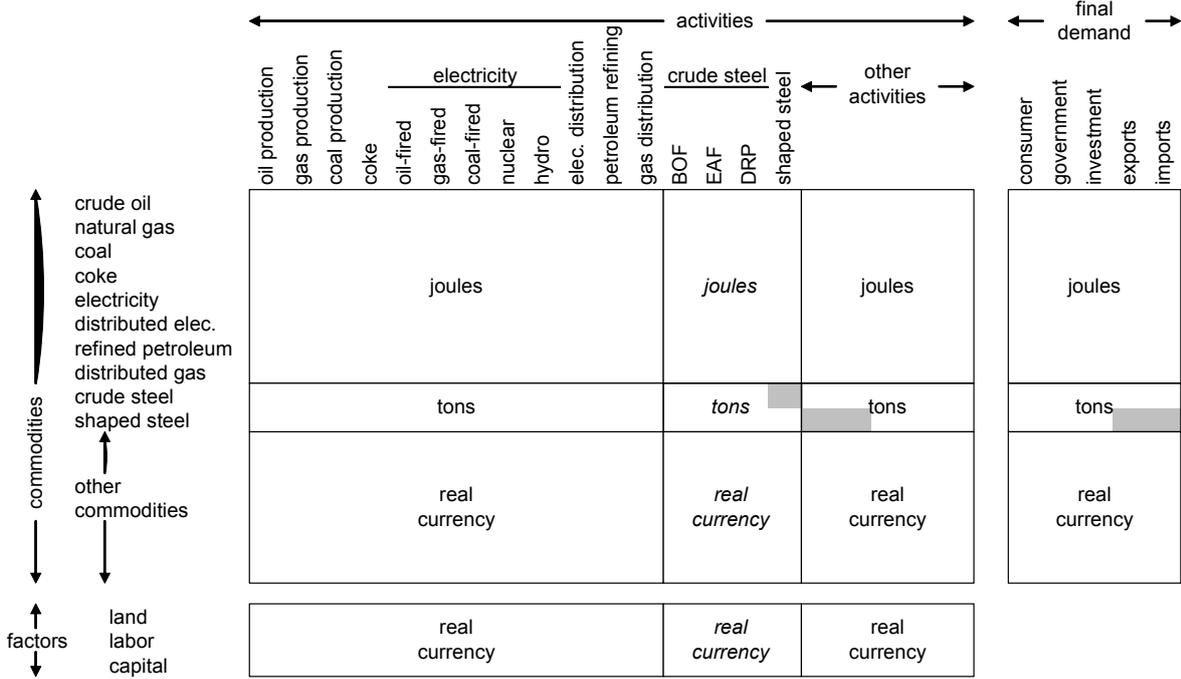


Figure 3.1 Organization of benchmark use table for Germany in 1995. Each row is a distinct commodity and each column represents production activities. Three distinct activities (technologies) are available for crude steel production: basic oxygen furnace (BOF), electric arc furnace (EAF), and a direct reduction process (DRP).

This data set can be used for either the technology-based approach or the aggregate CES approach: the only difference is that the columns under “crude steel” are combined to form a single aggregate technology for making steel in the aggregate production function approach. Further background on methods used to construct a benchmark data set for SGM is found in Sands and Fawcett (2005).

3.2.2 Technology-based approach

In the technology-based logit approach, each steel technology is first modeled as a fixed-coefficient (Leontief) production function. Then these production functions are combined in a logit nest. This approach has proven useful for the electricity generation sector in SGM-Germany (Schumacher and Sands, 2006).¹⁰ We construct an engineering cost description for each steel technology (see section 3.3.2); cost descriptions for technologies that operate in the model base year are embedded in the benchmark data set. The logit nesting structure for the steel technologies in this study is provided in Figure 3.2.

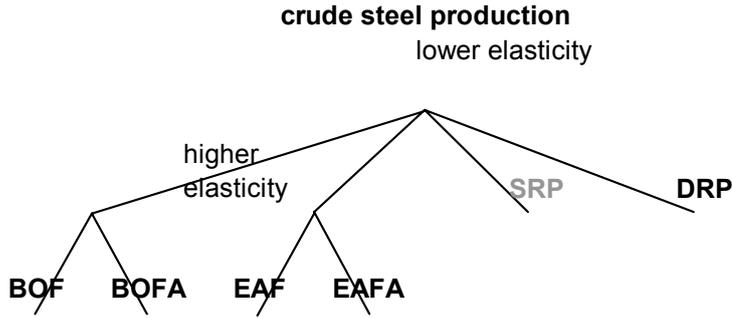


Figure 3.2 Nesting structure of steel technologies. Each leaf of the nesting structure is a fixed-coefficient technology: basic oxygen furnace (BOF), advanced BOF (BOFA), electric arc furnace (EAF), advanced EAF (EAFA), and a direct reduction process (DRP). The model has space for another advanced technology, smelt reduction process (SRP), but it is not presently populated with data.

The unit cost function for a fixed-coefficient technology j can be written as

$$C_j = \frac{1}{\alpha_{0j}} \sum_{i=1}^N \frac{p_i}{\alpha_{ij}} \quad (1)$$

where C_j is the unit cost or levelized cost per ton of crude steel. Levelized cost is a function of prices and technical coefficients α_{0j} , α_{ij} , $i=1, \dots, N$. N is the number of inputs to production. If the input is capital, the corresponding price is the annualized cost of capital, covering interest plus depreciation. During each model time step, new investment is allocated across steel technologies as a function of levelized cost. The share of output provided by each technology is determined by Equation (2),

$$s_j = \frac{b_j C_j^\lambda}{\sum_k b_k C_k^\lambda} \quad (2)$$

¹⁰ This approach could be generalized to a logit nest of CES technologies or a logit nest of nested CES technologies. Representing each technology as a Leontief production function is somewhat restrictive, as it does not allow input substitution possibilities within the technology that may exist in reality (Saunders, 2000b).

where C_j is the levelized cost per ton of crude steel, b_j is a calibration parameter to match base-year production, and λ determines the rate that one technology can substitute for another.¹¹ This formulation prevents knife-edge switching from one technology to another. The lambda parameter is actually an elasticity and can be expressed as

$$\lambda = \frac{\partial \left(\frac{s_i}{s_j} \right) \left(\frac{C_i}{C_j} \right)}{\partial \left(\frac{C_i}{C_j} \right) \left(\frac{s_i}{s_j} \right)} \quad (3)$$

A cost function for crude steel production using a logit nest can be written as

$$g(\mathbf{p}) = \sum_j s_j C_j \quad (4)$$

where the s_j are the logit shares from Equation (2) and the C_j are fixed-coefficient unit cost functions in Equation (1). The key parameter that determines the price response of iron and steel is λ . Technologies with lower unit costs provide a larger share of output. Technical change occurs mainly through changing shares of technologies, and not through changes in technical coefficients within production functions.

The technology-based approach presented here is in some ways similar to efforts by researchers who incorporate engineering-process representations of energy supply into general equilibrium models. The main difference is in the functional form used to distinguish technologies. McFarland et al. (2004), for example, use engineering information for a number of electricity technologies to parameterize a nested CES production function in a way that accounts for limits in thermodynamic efficiency and represents market penetration of technologies as their competitiveness changes. Similarly, Welsch (1998, 1996) embeds detail for existing electricity technologies in a CES functional framework. Pant (2002), Pant and Fisher (2004), and Li et al. (2003) use a generalized form of CES, the CRESH function

¹¹ The lambda parameter is set to -1.5 in the top nest of Figure 3.2, and to -15 in the lower nests of Figure 3.2.

(constant ratio of elasticities of substitution, homothetic) to aggregate a set of Leontief technologies. An important difference between a logit nest, as applied in our analysis, and a CES aggregate of Leontief technologies is that a logit nest preserves quantity balance while a CES function does not. In other words, the total quantity of steel production in a logit nest is always equal to the sum of steel production from the nested technologies.

Our approach differs from efforts by others to couple detailed engineering-process models, such as MARKAL, with multi-sector computable general equilibrium (CGE) frameworks (Schäfer and Jacoby, 2006, 2005; Proost and van Regemorter, 2000). By loosely coupling the two model types, they aim to establish consistency of parameters that determine substitution possibilities. Providing consistency remains a challenge, as the models are based on different data sets (value terms and physical flows) and have different analytical structures.

3.2.3 Aggregate production function approach

CGE models for analysis of climate policy generally use production functions that are well behaved over a wide range of relative prices, especially energy prices. A climate policy could drive energy prices, especially the price paid for coal, far outside the range of historical experience. The usual approach in CGE modeling is to represent each production sector as a single production or cost function. The CES functional form, or nested variations, is used more frequently than any other functional form. This form has the important property of being globally regular so that input demands can be calculated for any set of prices. It is possible to use more flexible functional forms, such as the translog, in a CGE model. However, they are more difficult to handle because they have additional parameters that require empirical support. Shoven and Whalley (1992) and Perroni and Rutherford (1995) provide further discussion on the choice of functional form in CGE models.

The key parameter in the CES function that determines response to a change in prices is the elasticity of substitution. The CES cost function is written as:

$$g(\mathbf{p}) = \frac{1}{\alpha_0} \left[\sum_{i=1}^N \left(\frac{p_i}{\alpha_i} \right)^r \right]^{1/r} \quad (5)$$

where unit cost is a function of prices and technical coefficients $\alpha_0, \alpha_i, i=1, \dots, N$. N is the number of inputs to production.¹² The elasticity of substitution is

$$\sigma = 1 - r \tag{6}$$

The physical input-output coefficients are functions of prices and technical coefficients

$$a_{ij}(\mathbf{p}) = \alpha_{0j}^{\sigma-1} \alpha_{ij}^{\sigma-1} \left[\frac{p_j}{p_i} \right]^\sigma \tag{7}$$

With this approach, we do not distinguish among the separate steel technologies, but combine the columns under “crude steel” in Figure 3.1 to form an aggregate technology. Technical coefficients are calibrated in order to match benchmark data for each activity at base year prices.¹³ Equation (7) clearly shows the relationship between input-output coefficients, relative prices, and the substitution elasticity.

Exogenous technical change is introduced by specifying a time path for the alpha coefficients in Equations (5) and (7). As the alpha coefficients increase, less of an input is needed to produce the same quantity of output and unit costs decline. We apply technical change independently to specific inputs, especially to labor and the energy carriers. The labor productivity parameter primarily determines the rate of economic growth. Similarly, the energy productivity parameters affect the future path of energy consumption and greenhouse gas emissions.

3.2.4 CGE framework

The benchmark data set described by Figure 3.1 provides base-year calibration data for a computable general equilibrium model for Germany, that we call SGM-Germany. The base

¹² Note that Equation (5) collapses to Equation (1) when $r = 1$.

¹³ CGE models are generally calibrated to a benchmark social accounting matrix for a single year. This year may not be representative (it could be during a recession). Therefore, it would make sense to allow the benchmark data set to be constructed using time-series data, but this is rarely done. However, a lot of progress has been made over the past decade to integrate energy balances into the benchmark social accounting matrix (e.g., Sands

year is 1995 and the model runs to 2050 in five-year time steps. SGM-Germany is a dynamic-recursive model of a small open economy.

Capital stocks are divided into five-year vintages and old capital cannot move between production sectors. Old capital is of the fixed-coefficient functional form and is retired at the end of its lifetime, anywhere from 20 to 40 years. We have assigned capital stocks in the iron and steel sector a lifetime of 25 years.¹⁴ Because of the time required for turnover of capital stocks, any change in relative prices, whether due to an exogenous change in oil prices or to a carbon policy, takes time to be fully reflected in model output.

Prices of oil, gas, and coal are given exogenously (FEES, 2007): the model can import as much of these fuels as desired at the given world price. However, a balance of payments constraint requires that any increase in imports of fuels be offset by exports of other goods. The balance of payments constraint is imposed by setting an exogenous capital flow during each model time step. In this study, the exogenous capital flow is set equal to its base-year level throughout the model time horizon. Therefore, the balance of payments constraint does not change over time and has little impact on overall production or consumption.

SGM-Germany contains 20 produced commodities. Besides the commodities shown in Figure 3.1, the model includes the following production sectors: agriculture, food processing, wood products, chemical products, non-metallic minerals, other metals, other industry, rail and land transport, other transport, and a large services category. All production sectors except electricity generation and crude steel production are represented by CES production functions.

3.2.5 Technical change

An important difference between the technology-based approach and the aggregate production function approach is the treatment of technical change over time. Both approaches assume exogenous technical change: the aggregate production function approach allows an annual percentage rate reduction in the quantity of inputs per unit of crude steel, while the technology-based approach relies on substitution of one technology for another over time.

and Fawcett 2005). This provides much greater realism, in terms of energy quantities and greenhouse gas emissions, than is possible without direct use of energy balances.

¹⁴ This refers to the average lifetime of capital stock in the iron and steel sector. Investment in retrofits of existing furnace technologies (vintages) can lead to much longer individual lifetimes (Worrell and Biermans, 2005).

In the aggregate CES approach, we assumed the following annual rates of technical change in the iron and steel sector for the following inputs: coal and coke, 0.5% per year; refined petroleum, 0.5% per year; electricity, 0.2% per year; natural gas, 0.5% per year; labor, 1.5% per year; other inputs to production, 0.1% per year (Sands and Fawcett, 2005). These rates of change begin in the model base year and continue at the same rate throughout the model time horizon.

In the technology-based approach, BOF and EAF are the only steel production technologies that operate in the model base year of 1995. However, advanced versions of these technologies (BOFA and EAFA), with lower energy requirements, are assumed available at a later point in time (see section 3.3.2 for exact specification). Because they use less energy, steel can be produced at lower cost and the advanced technologies replace the older technologies over time. A direct reduction process (DRP) also becomes available at a specified point in time and gains a share of the market in the base case.

3.3 Iron and steel technologies

We use iron and steel production in Germany as an example to demonstrate a methodology for embedding technology data into a general equilibrium economic framework. This section provides background on the main types of steel production processes and the data required to represent them in an economic model. We begin with a general description of alternative steel production routes and how they relate to the benchmark data set for SGM-Germany. We account for several distinct production routes with their inherent engineering characteristics. A mix of generic technologies, which do not reflect as much technological detail as is common in bottom-up engineering analysis, represents each production route. An economic analysis of these technologies requires data on all inputs to production, including energy, capital, labor, and materials.

3.3.1 Background on production routes

Iron and steel production is among the most energy-intensive industries in the majority of industrialized countries and is responsible for a large share of greenhouse gas emissions. Germany is a major steel producing country. With 46 million metric tons¹⁵ of crude steel produced annually, Germany is the largest producer in the European Union and ranks sixth

¹⁵ In the following, the term tons (t) shall always refer to metric tons.

worldwide, following China, Japan, the US, Russia and South Korea (data for 2005, IISI, 2006). Crude steel production in Germany in 2001 was responsible for approximately 52 million tons of CO₂ emissions and thus about one-third of industrial CO₂ emissions or 6% of economy-wide German CO₂ emissions (Buttermann and Hillebrand, 2001).

Two distinct iron and steel producing routes are currently in use in Germany: (1) the integrated route of producing crude steel in a two-step blast furnace/basic oxygen process based mainly on iron ore and coke, and (2) the electric arc furnace route based on scrap steel and electricity. They differ mainly with respect to fuel and raw material input, production technology and scale, and variety and quality of steel products. Production of crude steel in Germany is mainly through the conventional integrated blast furnace/basic oxygen (BF/BOF) route (70%) and to a lesser extent through the electric arc furnace (EAF) route (30%) (see Figure 3.3, WV Stahl and VDEH, 2005; Aichinger et al., 2001). As can be seen in Figure 3.3, the open hearth furnace technology (OHF) played a small role in Germany in the early years after reunification (1990-94) as a relic of outdated East German technology. Since it provides an obsolete, energy-intensive and inefficient production process (Phylipsen et al., 1998), plants using this technology were taken out of service soon after reunification.

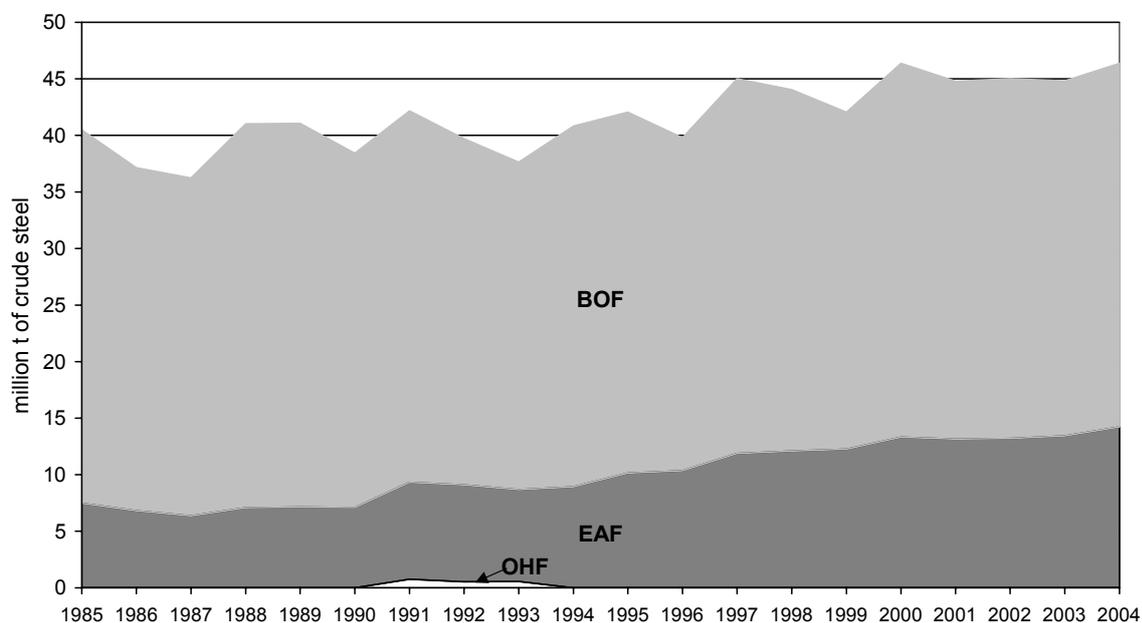


Figure 3.3 Crude steel production by process type, Germany 1985-2004

Figure 3.4 shows the main routes of steel production relevant for our analysis of German iron and steel production (adapted from Daniels, 2002; Worrell et al., 1997). The

number of processes required to produce crude steel differs for each technology path (production route). The currently used **primary steel route** requires coke, injected coal, and prepared iron ore in the form of sinter or pellets to produce pig iron in a blast furnace. The blast furnace itself is an efficient process but its main inputs, coke and sinter, are very energy-intensive (Daniels, 2002). To reduce energy consumption in the blast furnace, injected coal can partially substitute for coke, but coke is needed as a reduction agent. In a second step, pig iron is fed into the basic oxygen furnace (BOF) and converted into crude steel. The basic oxygen furnace is an exothermal process, i.e. it produces heat. Because of the excess energy, scrap can be added in the basic oxygen furnace as a substitute for pig iron to reduce energy consumption. For process physics reasons, however, the basic oxygen furnace is limited in the amount of scrap it can take, up to 35% (or 45% if pre-heated, Daniels, 2002). The share of scrap input into the basic oxygen furnace in Germany is around 18% (Statistisches Bundesamt, 2006) and thus lower than, for example, in the US with about 28% (USGS, 2006, 2004). Both blast furnace and basic oxygen furnace yield, to a varying extent, calorific gases as by-products that can be used in subsequent process steps. The primary steel route is therefore highly vertically integrated and optimized over the course of the production chain, e.g. from coke production to final product mix, which implies that it is most efficient at a large scale of production (Daniels, 2002).

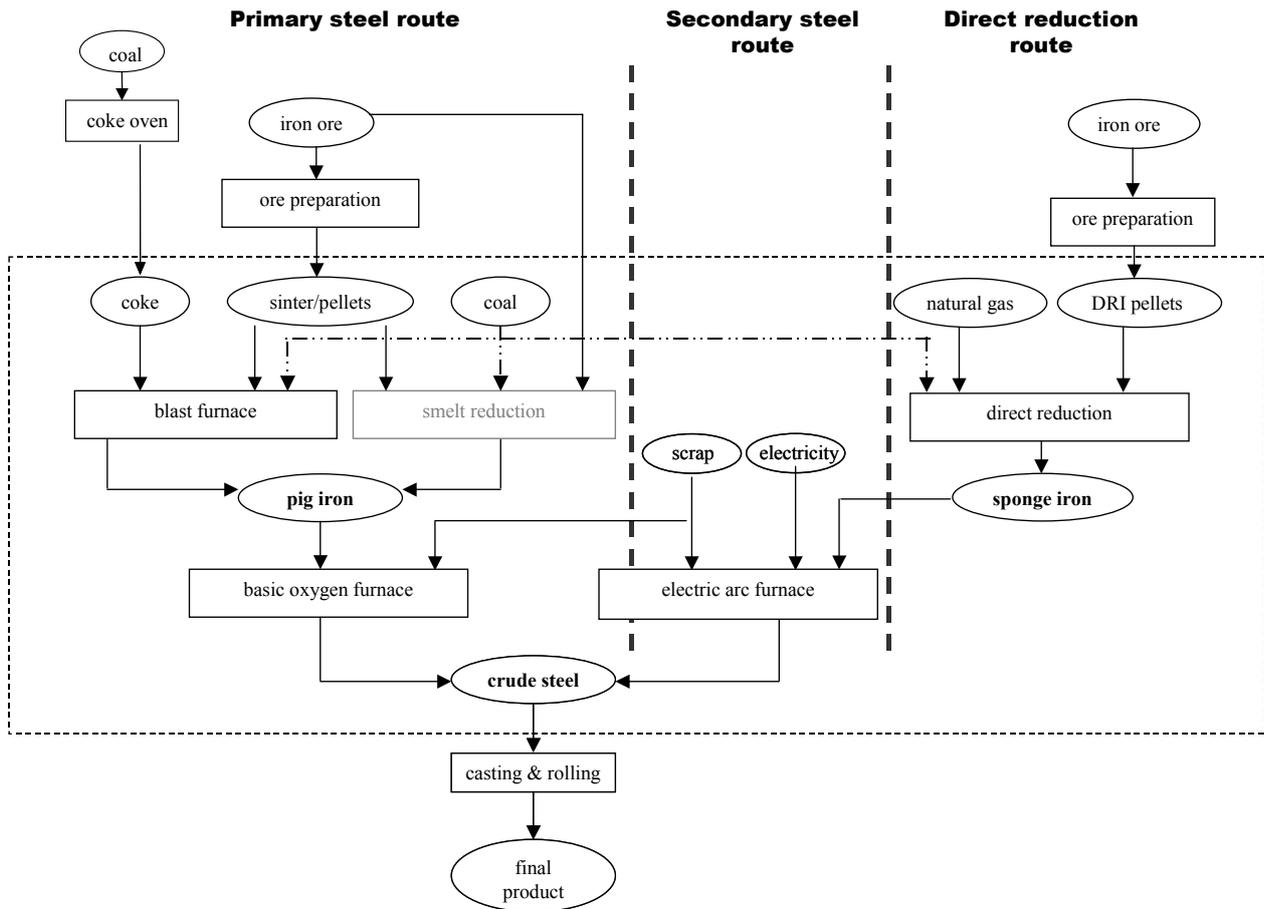


Figure 3.4 Iron and steel production routes. The dotted rectangle indicates the system boundary for the crude steel production process in SGM-Germany.

Another possibility for steel production is the **secondary steel route**, where recycled steel (scrap) melts into liquid steel in an electric arc furnace (EAF). This route is substantially less energy-intensive than the integrated route. Electricity is the main energy input into the electric arc furnace. The quality of EAF steel is typically not sufficient to produce highest quality products because of contaminants in the scrap (WEC, 1995). The introduction of new downstream processing (casting) technologies, however, allows EAF plants to compete in market segments that were traditionally reserved for integrated mills (Worrell and Biermans, 2005). A major advantage of scrap-based steel making is its lower energy consumption and flexibility. No products from other on-site installations are needed, and it can economically produce steel at substantially smaller scales than the integrated route. Scrap-based electric arc furnaces are often referred to as mini-mills.

Alternatively, sponge iron from a **direct reduction process** (DRP) can serve as a substitute for scrap and as a source of iron for steel production in an electric arc furnace (compare Figure 3.4). Adding primary iron sources, such as sponge iron, to the input charge

in an electric arc furnace reduces the adverse effects of contaminants in the recycled steel (Daniels, 2002). This has the advantage that the steel quality is improved compared to merely scrap-based EAF production. Besides quality improvement, direct reduced iron is also often used as an input if scrap is scarce and expensive (Schumacher and Sathaye, 1998). Scrap prices have been rather volatile in the last decade and may increase with rising world demand and tight supply (Metal Bulletin, various years; Ameling, 2005). The current direct reduction processes are mainly based on natural gas input, although some coal-based technologies also exist or are under development (Daniels, 2002; Knop, 2000; Lungen and Steffen, 1998; IISI, 1998; de Beer et al., 1998). The combined DRP/EAF route is more energy intensive than the scrap-only EAF route but less energy intensive than the integrated BF/BOF route. For optimal functioning, the DRP/EAF route requires prepared iron ore (DRI pellets). It is therefore more capital intensive and less flexible than mini-mill scrap-based EAF production. Some technologies based on fine ore rather than prepared iron ore exist and are being further explored (Knop, 2000). The DRP/EAF route has the potential to produce steel from any mixture of scrap and primary metals. In particular, it can use more than the maximum of 45% scrap as in the integrated route.

Currently, Germany has the only operating integrated (DRP/EAF) mini-mill in Europe. A direct reduction plant produces sponge iron, which, in equal shares with scrap, is fed into an electric arc furnace to produce steel (Schnabel, 2004). Because this direct reduction plant has a very small share in EAF-based steel production, we do not account for it separately in our analysis but include it in the conventional EAF technology category. In principle, direct reduced iron can also be used as a substitute in a basic oxygen furnace (Buttermann and Hillebrand, 2005; Lungen and Steffen, 1998; IISI, 1996). In our analysis, we allow direct reduced iron only to be used as an iron input and scrap substitute in the electric arc furnace. Similarly, pig iron is the only iron input into the basic oxygen furnace, complemented by scrap.¹⁶

Future innovative technologies for energy-efficient iron and steel making, such as advanced direct reduction and smelt reduction of iron ore, are investigated in the literature (de Beer et al., 1998; Luiten, 2001; Nil, 2003; Knop, 2000) but still surrounded by uncertainties with respect to their energy requirements, production costs, and time they will become commercially available. Those innovations focus on substituting away from upfront ore

¹⁶ This is in line with production route presentations as in Daniels (2002), Worrell et al. (1997), WEC (1995).

preparation and coke making, as these processes are both capital and energy intensive. Because of data availability, we include an advanced natural gas based direct reduction technology in our analysis (the HYL DR process; Knop, 2000, see next section), but no smelt reduction technology. The latter is therefore shaded in light grey in Figure 3.4. Smelt reduction avoids coke making in the pig iron production step and therefore reduces energy requirements compared to the conventional blast furnace (IISI, 1998). Smelt reduction (such as the COREX technology) is commercially available but at a rather small-scale and with relatively high capital costs (Fruehan, 2005). More advanced smelt reduction technologies, such as the Cyclone Converter Furnace (CCF) technology, are under research and development but not in commercial use yet (Lüngen et al., 2001). Production costs of these technologies are expected to be lower than in the conventional blast furnace route (de Beer et al., 1998; Daniels, 2002).

Various studies in the literature assess the potential for energy efficiency improvement and CO₂ emissions reduction in the iron and steel industry for existing and future technologies (Aichinger and Steffen, 2006; Rynkiewicz, 2005; Kim and Worrell, 2002; Worrell et al., 2001; Phylipsen et al., 1998; WEC, 1995). They agree that substantial energy efficiency improvement possibilities exist, but depending on their assessment of current energy consumption, the potential for efficiency improvements varies. Because iron and steel production is a large point source of CO₂ emissions, it is considered well suited for CO₂ capture and storage (CCS). CCS technologies for electricity production are well researched in the literature and can potentially be applied to the iron and steel industry (IPCC, 2005; Daniels, 2002). Currently, we incorporate CCS technologies for the electricity sector and not yet for the iron and steel sector.

To produce finished steel, crude steel must be cast, rolled, and shaped. Technologies for casting, rolling, and further processing of crude steel can be considered to be the same for different crude steel production routes (Aichinger et al., 2001). Substantial energy savings are possible with new casting technologies (e.g. continuous casting or thin-slab casting), which may also improve the quality and the mix of steel products and, consequently, open up market segments to secondary steel producers (Worrell and Biermans, 2005; Daniels, 2002; Worrell et al., 2001). Currently, we do not distinguish between different technologies for casting, rolling and shaping in our analysis, but draw a system boundary at the level of crude steel production (see Figure 3.4). Decomposing steel output into different products and into the required casting, rolling and finishing processes adds a substantial level of complexity to the

analysis.¹⁷ Daniels (2002) is a good starting point in providing cost and performance data for these processes and technologies.

The structure of the benchmark data set for SGM-Germany (Figure 3.1) reflects the fact that there are many ways to make crude steel, but further processing of steel is relatively independent of the crude steel technology. This can be seen in Figure 3.1, where the benchmark data include separate rows for crude steel and shaped steel, indicating that these are separate commodities in the model with separate market prices. The columns in Figure 3.1 indicate that there are three distinct activities for making crude steel but only one for shaped steel. This implies that, in line with other studies, we assume crude steel to be a homogenous product (Lutz et al., 2005; Hidalgo et al., 2005; Ruth and Amato, 2002). This is a simplifying assumption that neglects quality differences in crude steel.

3.3.2 Production costs and energy use for iron and steel

Detailed information on production costs and energy use of German iron and steel making is shown in Table 3.1. These data provide the basis for an engineering cost description of iron and steel technologies in SGM-Germany. Five iron and steel technologies are represented: basic oxygen furnace, advanced basic oxygen furnace, electric arc furnace, advanced electric arc furnace, and a direct reduction process. The direct reduction process assumes that an equal share of scrap and direct reduced iron is fed into an electric arc furnace. The data for the direct reduction process refer to an advanced natural gas based technology (HYL DR) that is not commercially used in Germany yet. It is assumed to be available by 2015 (Knop, 2000).

For the existing blast furnace/basic oxygen furnace route (BOF), it is assumed that sinter, pellets and lump ore are used as inputs at a share 4:2:1 (Knop, 2000). The share of scrap input into existing basic oxygen furnaces is set at 18%. Advanced BOF and EAF (BOFA and EAFA) are assumed to be more efficient in terms of energy use than their currently available counterparts. The efficiency improvement can be achieved either by stock turnover, and thus investment into new and more efficient stock, or by retrofitting existing

¹⁷ In particular, we would need to acquire a good understanding of subsequent use of steel products. The input-output framework in the benchmark data set in SGM-Germany requires allocation of steel products to various users, such as other industry, transport, electricity distribution, food processing, agriculture, export etc., and we would need to assign a share of each product (i.e. output from each process route) to be used by each user.

plants.¹⁸ In SGM-Germany, we do not explicitly distinguish these two options but assume that retrofits, just as investment into new stock, count as additions to the capital stock and are associated with the same costs. Additionally, changing operation modes of existing plants contributes to efficiency improvements, such as changing the composition of feedstock by replacing sinter with pellets or replacing coke with injected coal in the blast furnace, or increasing the share of scrap in the basic oxygen furnace.

Advanced technologies in SGM-Germany are discrete technologies that are assumed to be available for operation in Germany starting after 2010. In principle, most of the technologies are available today with some already being in operation, mostly in developing countries where demand for steel products is soaring (Daniels, 2002; Lungen et al., 2001). Steel demand in industrialized countries is different both in terms of quality and quantity. Declining or stable demand provides conditions that make large scale capacity expansion via introduction of new technologies unlikely. For the last decade, the number of steel plants in Germany has declined while at the same time capacity utilization has increased from 83% in 1995 to almost 90% in 2004 (WV Stahl and VDEH, 2005). In BF/BOF steel production, the retirement of coke ovens, which are highly capital and fuel intensive, has an important influence on capital turnover and the introduction of new production routes. For Germany and the UK, average coke oven plants are of relatively young age compared to most European countries, and the choice of either rebuilding a coke oven or adopting different production processes will start to come at around 2010 (Daniels, 2002). The characteristics we assume for BOFA, EAFA, and DRP are based on more advanced versions of the currently available technologies as they are expected to evolve (Knop, 2000; Stubbles, 2000). Note that all the technologies reflect engineering characteristics but are stylized in order to be included in a general equilibrium-modeling framework. Each technology should be viewed as a generic technology of its kind.

Table 3.1 presents energy inputs by fuel type as both quantities and values. In line with the source data, the values are presented in US\$. Energy use and costs in BOF, advanced EAF (EAFA) and DRP technologies are based on Knop (2000). Advanced BOF (BOFA) is based on the assumption of a 10% energy efficiency improvement, while current EAF energy use is based on data provided by the German steel association (WV Stahl and VDEH, 2005). Total

¹⁸ In line with Worrell and Biermans (2005), retrofit refers to an upgrade of existing capacity by implementing energy-efficient technologies or measures. Worrell and Biermans find in a case study for the US that two-thirds

production costs are the sum of energy, raw material, labor and capital costs. Labor and capital costs are based on Knop (2000). Raw material costs include non-energy related costs for iron ore, pig iron, sinter, pellets, scrap and other materials to produce crude steel. They have the highest share in total costs. A price is attached to each material input independent of whether it is produced on-site or bought from a different source. For price information, see Knop (2000). Material costs are driven mainly by scrap prices in the EAF, EAFA, and DRP/EAF production routes. The energy contained in each of the material inputs (and its related costs), such as for pellets or sinter, is separately accounted for as energy inputs to crude steel production. In line with Knop (2000), investment costs are discounted over a 10 year accounting lifetime at a rate of 8% in Table 3.1.

Capital stock lifetime in SGM-Germany is set to 25 years, which aims to reflect average equipment lifetime of steel technologies. The lifetime used by Knop (2000) is much lower because it is based on a financial depreciation schedule. Similarly, the discount rate (internal rate of return) used by Knop (2000) is higher than the interest rate resulting in SGM-Germany. The data in Table 3.1 reflect how technologies are described in Knop (2000). We apply our own assumptions to transform the original cost data to a format suitable for a CGE analysis of Germany. Moreover, production costs differ slightly when converted to Euros using Germany-specific fuel and electricity prices.¹⁹ CO₂ emissions in Table 3.1 are calculated as direct emissions from fossil fuel use and indirect emissions from electricity input based on a typical coal-fired power plant in Germany with emissions of 0.7 kg CO₂/kWh.²⁰

of the achieved energy savings in EAFs between 1990 and 2002 were due to new construction and one-third due to retrofit.

¹⁹ For example, in 2010 the following fuel prices apply in SGM-Germany: natural gas 4.71 euro/GJ, coal 1.76 euro/GJ, electricity generation 5.03 euro cent/kWh, electricity distribution 10.08 euro cent/kWh.

²⁰ Note that the emissions rates reflect exogenous assumptions here to visualize CO₂ emissions resulting from different technologies to produce crude steel. In SGM-Germany, the carbon factor of electricity production is endogenous according to the generation mix in each time step. Emissions from coke production are not allocated to steel production; however, emissions that result from the use of coke, i.e. the carbon contained in coke, are accounted for.

Table 3.1 Cost structure of iron and steel technologies

| | Units | BOF | BOFA | EAF | EAFA | DRP |
|---------------------------|-------------------------|---------------|---------------|---------------|---------------|---------------|
| Electricity | kWh | 223 | 201 | 512 | 350 | 385 |
| | US\$/tcs | 5.13 | 4.87 | 11.78 | 8.05 | 8.85 |
| Fossil fuels | | | | | | |
| Coal | GJ | 4.54 | 4.08 | 0.08 | - | - |
| | US\$/tcs | 10.55 | 10.23 | 0.18 | | |
| Coke | GJ | 9.88 | 8.89 | 0.01 | - | - |
| | US\$/tcs | 38.02 | 36.88 | 0.04 | | |
| Nat. Gas | GJ | - | - | 0.34 | - | 5.51 |
| | US\$/tcs | | | 1.29 | | 21.17 |
| Capital | US\$/tcs | 38.75 | 38.75 | 11.92 | 11.92 | 23.12 |
| Labor | US\$/tcs | 16.82 | 16.82 | 3.89 | 3.89 | 5.79 |
| Materials | US\$/tcs | 86.59 | 86.59 | 149.09 | 149.09 | 125.10 |
| Energy Credits | US\$/tcs | -9.67 | -9.67 | | | |
| SUM | US\$/tcs | 186.19 | 184.48 | 178.19 | 173.96 | 184.03 |
| Emissions | | | | | | |
| direct from fossil fuels | kg CO ₂ /tcs | 966 | 937 | 25 | 0 | 273 |
| indirect from electricity | kg CO ₂ /tcs | 156 | 148 | 359 | 245 | 269 |

Note: Assumed electricity price 2.3 cent/kWh, natural gas 3.84 US\$/GJ, coal 2.32 US\$/GJ, coke 3.85 US\$/GJ, plant lifetime 10 years, interest rate 8%. Scrap price at 115.38 US\$ per ton. Source for BOF, EAFA and DRP: Knop (2000), DRP assumes 50% scrap input, 50% direct reduced iron into an electric arc furnace. EAF: WV Stahl and VDEH (2005). Emissions: indirect emission from electricity based on typical coal fired power plant in Germany 0.7 kg CO₂/kWh. tcs – tons of crude steel.

3.4 Analysis and results

To demonstrate the operation of iron and steel production, several carbon policy scenarios are considered. The scenarios are intended to provide insights to the European Union CO₂ emissions trading system, but not to replicate all its features. The CO₂ prices are applied to the electric power sector, oil refining, coke production, and energy-intensive industries (i.e. those covered by the EU emissions trading scheme). Each policy scenario is simulated as a constant CO₂ charge instead of a price resulting from a cap and trade system in the European Union. Revenues from the CO₂ price are returned as a lump sum to a representative consumer.²¹ Our policy analysis consists of four constant-price scenarios at 10,

²¹ This version of SGM has a single representative consumer that purchases consumer goods and government services. Lump sum recycling to this consumer has little impact on the relative shares of economic production going to consumer goods and government services. We do not attempt to compare this method of recycling to

20, 30 and 50 € per ton of CO₂ starting in 2005. For the latter two scenarios, the CO₂ price is introduced in 2005 at 20 € per ton of CO₂ and increased to 30 and 50 € respectively by 2010. In addition, we conduct a scenario with a stepwise CO₂ price increase of 10 € in 2005, 20 € in 2010, and so on up to 50 € in 2025.

Each policy scenario is run for the CES representation of iron and steel and for the technology-based approach. The results of both these approaches are presented in the following sections. We start with detailed results from the technology-based approach (section 3.4.1), then move on to a comparison of the aggregate CES and technology-based approaches (section 3.4.2), and finally to economic and emissions results for the whole economy (section 3.4.3).

3.4.1 Technology-based analysis

The technology-based approach allows us to take a closer look at the structure of iron and steel production and its development over time. We first present a base case for iron and steel production in Germany through 2050 that includes a mix of technologies. Then we discuss the response of the various iron and steel technologies to a range of CO₂ prices. The technology response depends directly on the way that levelized cost changes as a function of the CO₂ price.

Production of crude steel in Germany in a base case, i.e. without any carbon policy, is shown in Figure 3.5. Advanced technologies come in after 2010 and capture a share of output in the base case as capital stocks retire and investment in new and less expensive technologies or in retrofits picks up. The mix of technologies after 2010 is the same as in the logit nest in Figure 3.2. Most of the conventional EAF technology is replaced by the advanced version (EAFA) by 2050. Similarly, investment in advanced BOF replaces old capital stocks of BOF and takes up an increasing share of output over time. At the same time, it competes with the new natural gas based direct reduction process (DRP). The DRP technology is an electric arc furnace technology that is based on a combination of scrap and sponge iron inputs and produces high quality steel, which directly competes with steel from the BOF route. It therefore partly replaces existing BOF, and to a lesser extent EAF, and accounts for most of the increase in iron and steel production. It is constrained by increasing natural gas prices and scrap availability. Scarcity of high and medium quality scrap may lead to increased scrap

other fiscal arrangements that might be more likely in practice such as recycling to the government or

prices in the future. This would then affect the share that DRP and EAF technologies hold in the future. In our analysis, scrap prices are assumed to remain at their 2004 level.²²

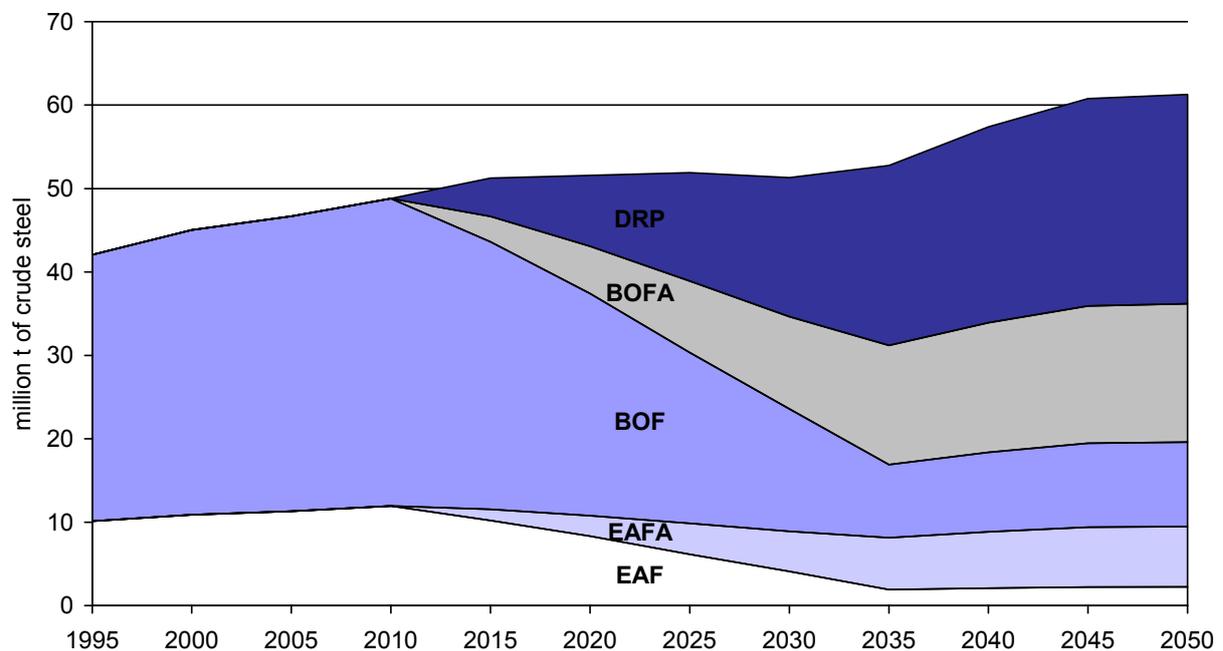


Figure 3.5 Production of crude steel through 2050 in a base case for Germany. Steel production occurs with basic oxygen furnace (BOF) and electric arc furnace (EAF) technologies before 2010. Advanced technologies are introduced after 2010, including advanced versions of BOF and EAF, and a direct reduction process (DRP).

A scenario with a stepwise increase in CO₂ prices was constructed so that we could plot the levelized cost of each iron and steel technology as a function of the CO₂ price. The technologies vary in their carbon intensity and therefore vary in the rate that levelized cost changes with respect to a CO₂ price. Figure 3.6 depicts the development of levelized costs for five technologies (BOF, BOFA, EAF, EAFA, DRP) over time and with a stepwise increase of the CO₂ price.

Besides scrap prices, levelized costs of crude steel production increase over time for two main reasons: because of rising fuel prices (coke, coal, natural gas) and because of carbon policies. Technologies that use more carbon intensive fuels, such as coke and coal, experience

distributing the majority of emissions rights to current emitters.

²² We simulate the adoption of technologies with their inherent cost, efficiency and availability characteristics as laid out in section 3.3.2. Different assumptions on technology specifications, in particular on the time of deployment, on costs and on quality differences in crude steel, would likely lead to different output shares in the simulation.

a higher increase in levelized costs of production than technologies that use less carbon intensive fuels. The incline of BOF technologies is steepest reflecting the higher carbon intensity. Levelized costs of the DRP technology are initially higher but break even with conventional and advanced BOF technology at a fairly low CO₂ price. This implies that their deployment is more restricted by the time they become available than by cost competitiveness. As shown in Figure 3.5, they take up a share of output even in the base case as soon as they become available after 2010. Because of relatively high electricity prices in Germany, the conventional EAF technology is slightly more expensive than the other technologies in the beginning, but is less sensitive to increases in CO₂ price and soon becomes economically competitive. The gap between levelized costs of BOF and other technologies widens as higher CO₂ prices are introduced.

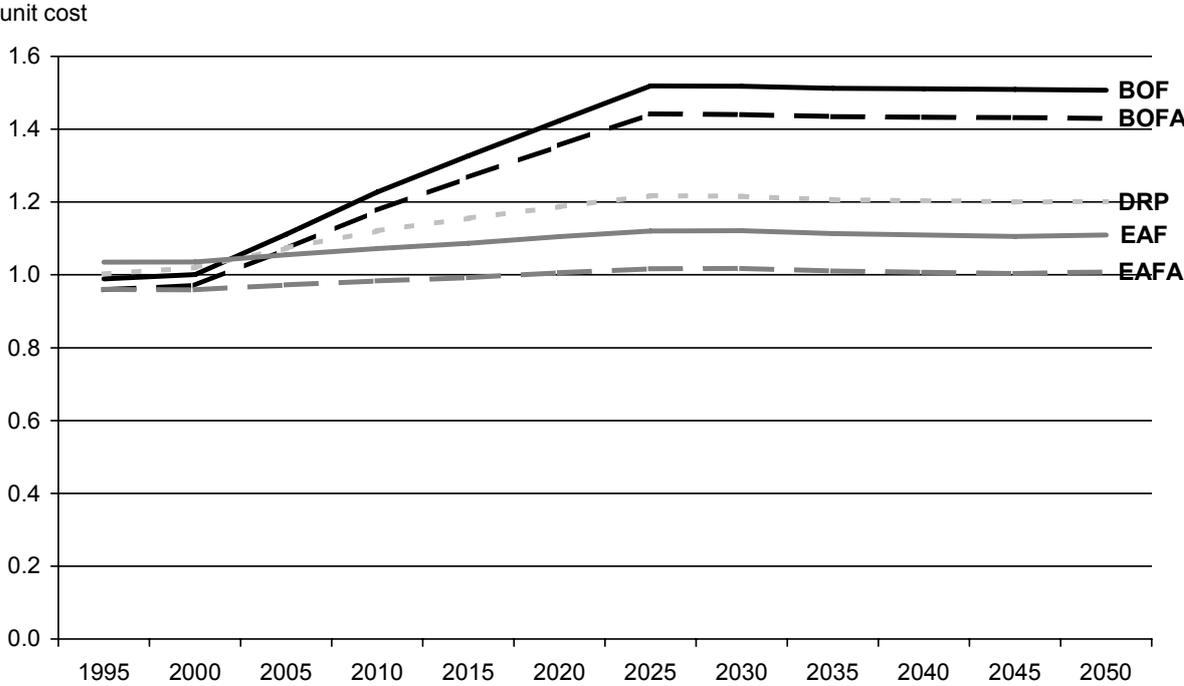


Figure 3.6 Development of levelized costs for five technologies (BOF, BOFA, EAF, EAFA, DRP) over time and with a stepwise increase of the CO₂ price (2005=10€/t CO₂, 2010=20€/t CO₂, 2015=30€/t CO₂, 2020=40€/t CO₂, 2025=50€/t CO₂). Levelized costs are indexed to the average cost of crude steel production in the base year (cost index equals 1 in 1995).

The effect on the structure and development of iron and steel production by technology can be seen in Figure 3.7. In 2020, some of the old capital stock will have been replaced by investment into advanced technologies. Production from BOFA, EAFA and DRP takes up an

increasing share in total iron and steel production. With a higher CO₂ price, steel output declines for the coke-intensive BOF technology, but increases slightly for the more electricity-intensive EAF and EAFA technologies. Emissions from electricity are accounted for in the electricity sector, where the CO₂ price is applied and added onto the price of electricity according to the carbon intensity of the electricity generation mix. Thus, the EAF and EAFA technologies face higher electricity prices. The increase in electricity prices for EAF steel, however, is not as pronounced as the increase in costs related to coke and coal use for carbon-intensive BF/BOF steel. By 2030, as the capital stock turns over, more and more advanced technologies come into production. With a higher CO₂ price, the shifts we noticed in 2020 are more distinct in 2030. The effect of the CO₂ price on DRP production is very small. With a mixed input of natural gas and electricity the effect is similar to EAF steel production.²³

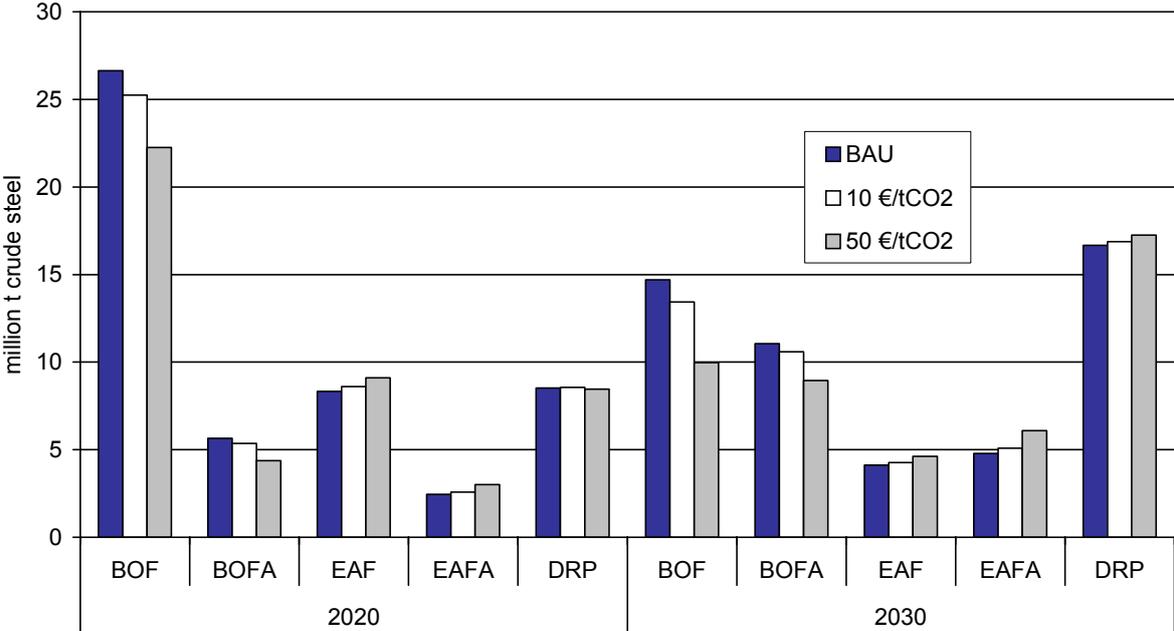


Figure 3.7 Simulated production of crude steel in 2020 and 2030 at three CO₂ prices: zero €/t CO₂ or business as usual (BAU), 10€/t CO₂, and 50€/t CO₂

²³ The result of a small response to an increase in energy related costs for EAF corresponds with earlier econometric estimations, for example, by Boyd and Karlson (1993), who find that non-price factors, such as technical change and potential costs reductions have a larger influence on the timing of technology adoption than energy prices.

3.4.1.1 Sensitivity analysis

We conduct a sensitivity analysis for high natural gas and high scrap prices. For illustration, we include three sensitivity cases relative to the base case: i) with respect to increased natural gas prices (assumed to be 30% higher than in base case in 2005, 50% in 2010, 70% in 2015, 90% in 2020 and 100% 2025 and thereafter; all relative to the base case); ii) with respect to increased scrap prices (assumed to more than double to 250 US\$/t scrap from 2005 on); and iii) with respect to both increased natural gas and scrap prices (combined effect of i and ii). In all cases no CO₂ price is applied. The sensitivity analysis reveals that the output of DRP is, as expected, quite sensitive to an increase in natural gas and scrap prices. Figure 3.8 shows the effects on output from DRP as percentage reduction in output compared to the base case. The illustrative specifications of increases in natural gas or scrap prices reveal a substantial decrease in output from DRP steel production for each sensitivity case. Independent of these exact specifications, which are subject to high uncertainties, it can be deducted that a combined increase in natural gas and in scrap prices has an almost cumulative, and thus most deteriorating, effect on output from DRP.

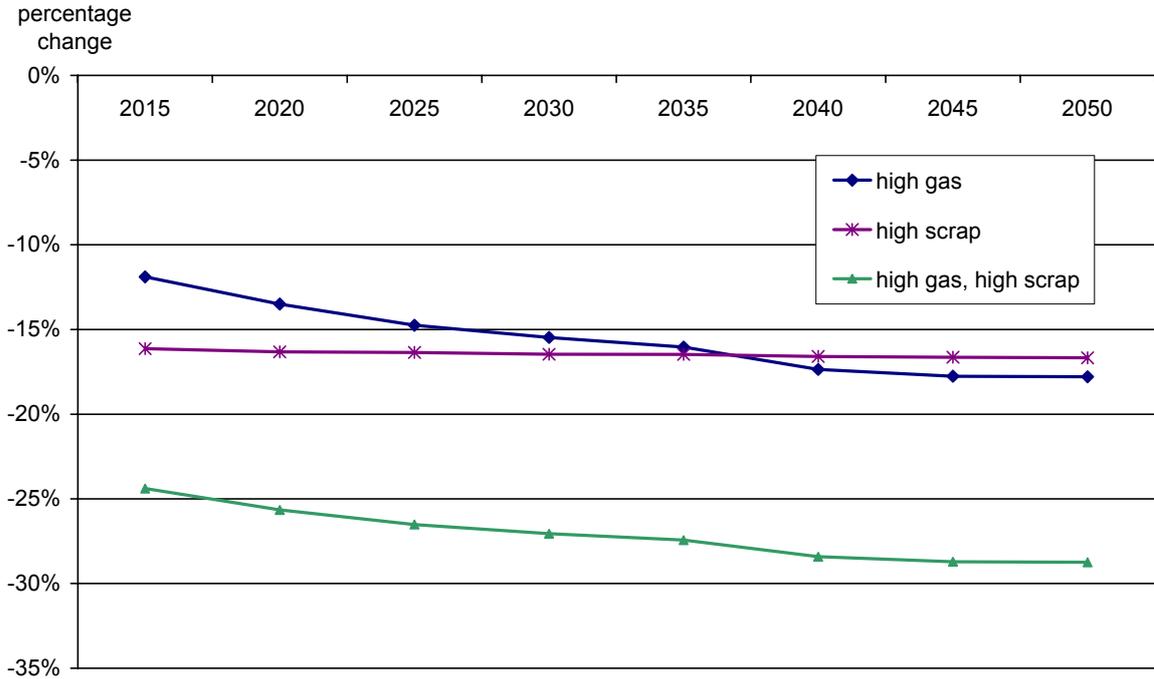


Figure 3.8 Percentage change in crude steel output from direct reduction process/electric arc furnace production (DRP/EAF) in three sensitivity cases relative to the base case. Sensitivity runs i) with respect to increased natural gas prices (assumed to be 30% higher than in base case in 2005, 50% in 2010, 70% in 2015, 90% in 2020 and 100% 2025 and thereafter; all relative to the base case); ii) with respect to increased scrap prices (assumed to more than double to 250 US\$/t scrap from 2005 on); and iii)

with respect to both increased natural gas and scrap prices (combined effect of i and ii). In all cases no CO₂ price is applied.

For the EAF technologies (EAF and EAFA, see Figure 3.9) the picture looks differently. In accordance with their input structure, i.e. mainly scrap based, no use of natural gas, they respond highly to changes in the assumptions about scrap prices. A higher scrap prices leads to a reduction in output of EAF steel. On the contrary, an increase in natural gas price, and its related reduction in output from DRP, induces an increase in output from EAF technologies compared to the base case. EAF based steel production partly compensates for the reduction of DRP based steel production. The combined effect of an increase in natural gas and in scrap prices on EAF based crude steel output is somewhat counterbalancing and depends on the exact specifications of price increases.

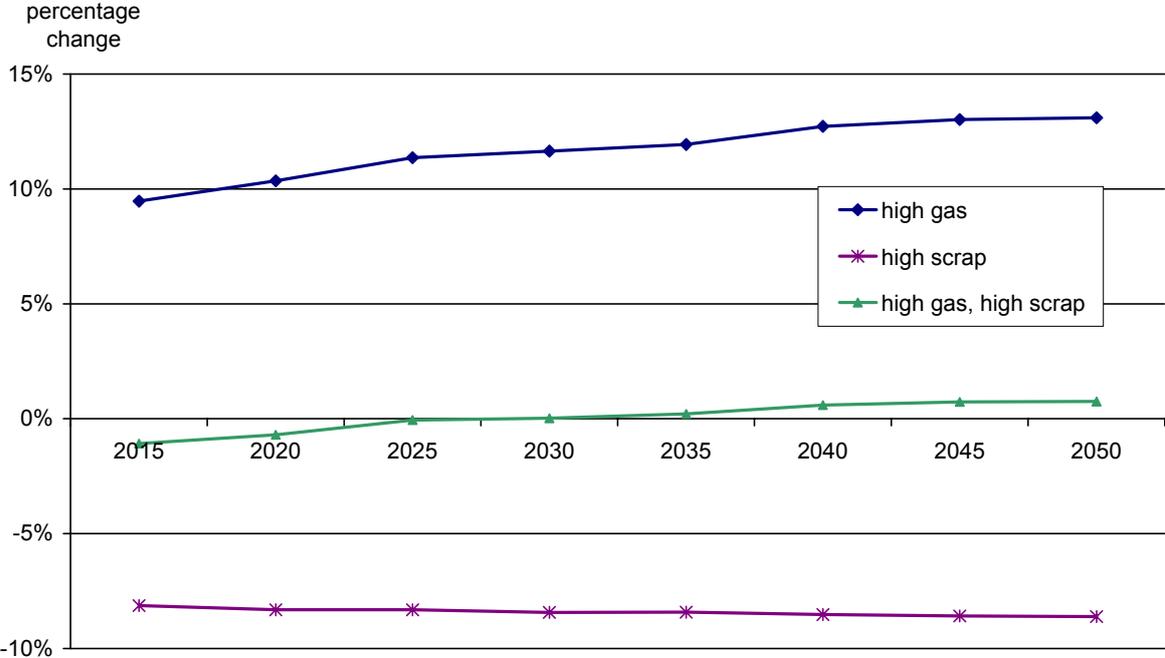


Figure 3.9 Percentage change in crude steel output from advanced electric arc furnaces (EAFA) in three sensitivity cases relative to the base case. Sensitivity runs as above (Figure 3.8).

The sensitivity runs also reveal effects on total crude steel output. An increase in natural gas price (*ceteris paribus*) leads to a reduction in total crude steel output and a higher share of both EAF and BOF based production (current and advanced). A simultaneous increase of both scrap and natural gas prices also leads to a reduction in total crude steel output, partly compensated for by an increase in BOF based production (BOF and BOFA).

3.4.2 Aggregate CES versus technology-based approach

This section compares results for the technology-based approach (LOGIT) and the aggregate CES approach. The same carbon policies are applied to both approaches, and the policies result in similar effects on production levels of iron and steel. Production increases over time, but to a lesser extent at higher CO₂ prices.

Because the CES approach does not distinguish between different technologies, we cannot compare the technology mix to produce iron and steel. Instead, we take a closer look at the energy inputs to iron and steel production, which reflects the underlying technologies and their distinct energy input structure. Energy input to iron and steel develops differently for the two approaches, over time and in response to a CO₂ price. Figure 3.10 shows specific energy input, in gigajoules per ton of crude steel, into iron and steel production in the base year and in year 2010. While in the base year, both approaches show the same specific energy consumption, the picture has changed by the year 2010. Specific energy consumption is lower in the CES approach and decreases with higher CO₂ prices.

The differences in specific energy consumption are due to the assumptions on technological change in the two approaches. As explained in section 3.2.5, exogenous assumptions on energy efficiency improvement are taken in the aggregate CES approach. They imply an annual decrease in energy consumption with respect to each individual fuel in a continuous way. Assumptions on technological change do not relate to specific technological characteristics. On the contrary, the approach with specific technologies (technology-based approach) uses assumptions about current and future technologies that are explicitly based on engineering data and allows for substitution of one technology for another over time. New technologies come into the model after the year 2010. No efficiency improvement is applied to the existing capital stock. Therefore, the reduction in energy input to iron and steel production in the base case is nil in the technology-based case (LOGIT) compared to the base year. Specific energy input in the technology-based case decreases with a higher CO₂ price. This is due to a shift in production technologies based on a change in levelized costs of production. Coal-intensive iron and steel production becomes relatively more expensive with a higher CO₂ price than natural gas or electricity based iron and steel production. However, the price response in 2010 is limited by the rate that existing capital stocks retire.

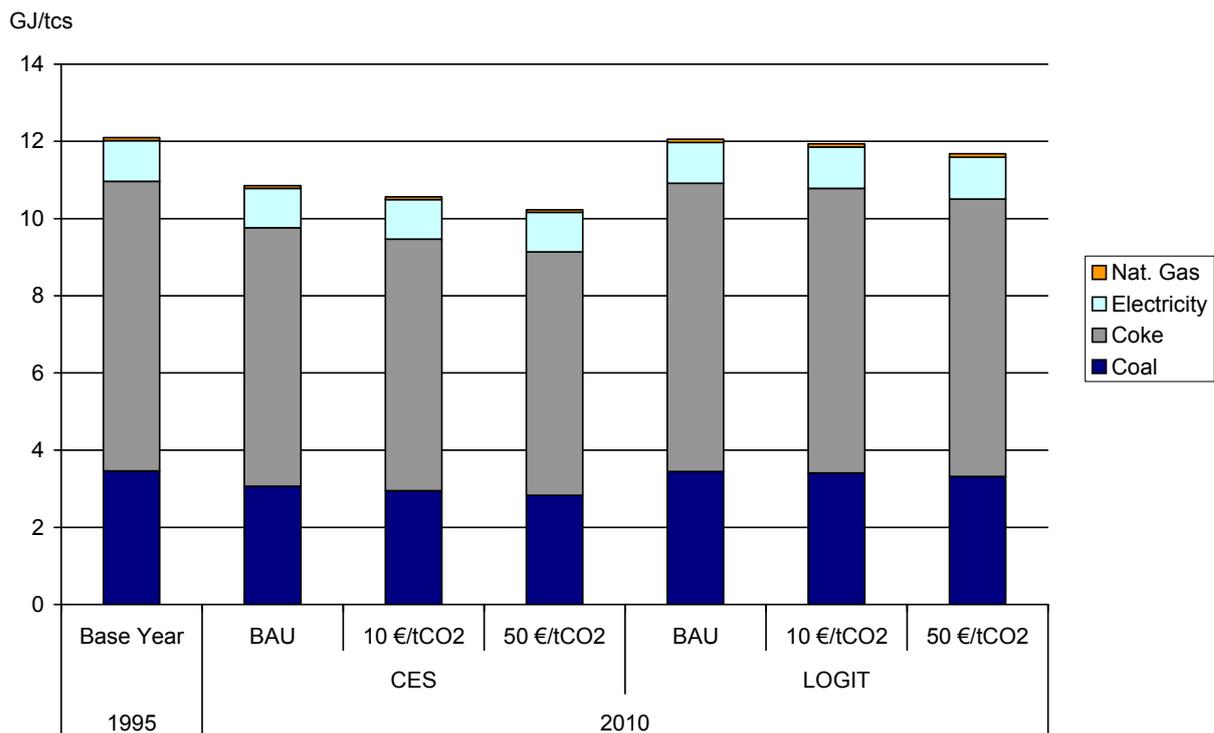


Figure 3.10 Specific fuel input to iron and steel production, base year and 2010. Units are gigajoules (GJ) per ton of crude steel. LOGIT refers to the technology-based approach, CES to the aggregate CES approach.

After 2010, new and more advanced technologies become available in the technology-based approach. They change the structure of iron and steel production depending on their relative production costs.

Figure 3.11 shows specific energy input to iron and steel production in the year 2030 for the aggregate production function approach (CES) and for the technology-based approach (LOGIT). Specific energy consumption decreases over time and with higher CO₂ prices for both the CES and the LOGIT approach. The response to higher CO₂ prices is more pronounced in the CES approach; this depends directly on the assumed elasticity of substitution ($\sigma = 0.3$). We can vary this response simply by changing the substitution elasticity. The CES approach is essentially locked into the same pattern of fuel inputs over time and in response to a carbon price. For this reason, almost no natural gas is used in the CES approach. In the technology-based approach (LOGIT), however, a higher CO₂ price induces production technologies to shift away from coal- and coke-intensive technologies (BOF) towards natural gas-intensive technologies (DRP). Thus, the average carbon intensity, per unit of crude steel, declines. There are some similarities in the carbon price response of the two approaches. Coke use dominates iron and steel production; yet, coal and coke

consumption per unit of crude steel declines substantially. Electricity consumption remains relatively constant in both approaches.

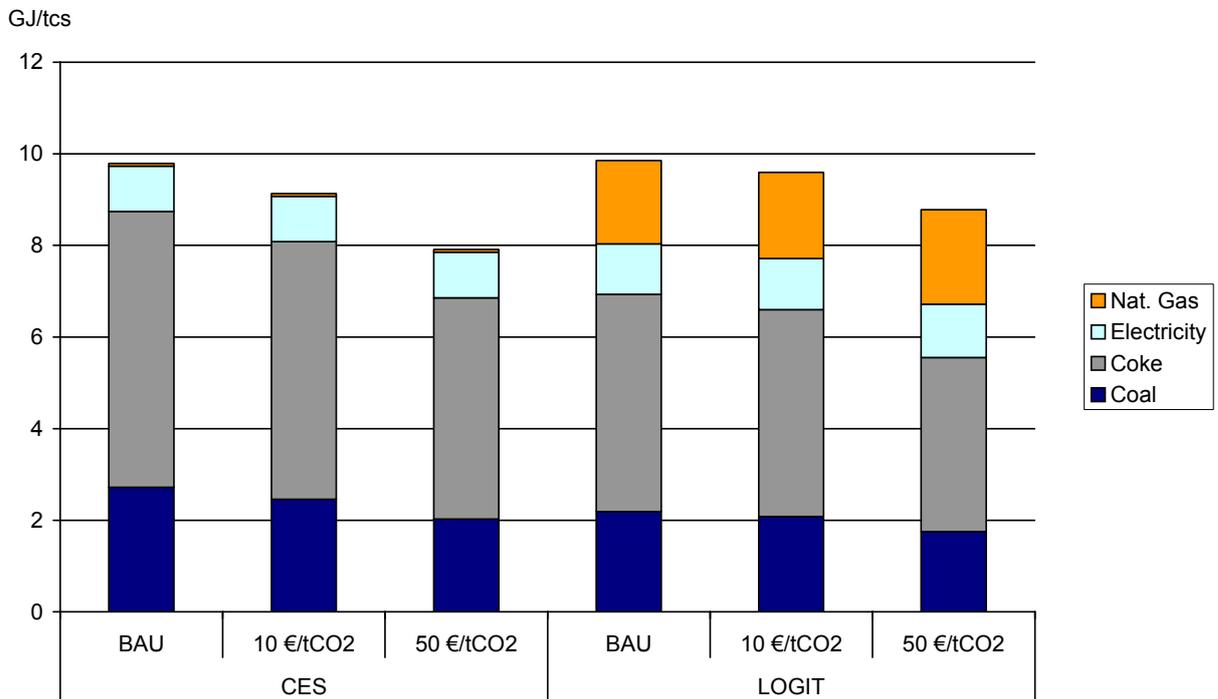


Figure 3.11 Specific fuel input to iron and steel production, year 2030. Units are gigajoules (GJ) per ton of crude steel. LOGIT refers to the technology-based approach, CES to the aggregate CES approach.

To summarize, we see a development in the CES approach that depends primarily on base year fuel input structure and the assumptions about fuel specific technological change over time. Depending on the assumed rate of technological change, energy intensity decreases more or less rapidly. No fuel switching other than that allowed by the input substitution elasticity can occur. If the substitution elasticity is relatively low, the base year structure dominates future development of energy use.

The technology-based approach (LOGIT) provides a greater flexibility with respect to structural change in steel production and its inputs. It allows for new technologies with different input characteristics to compete with existing technologies. Thus, it decouples base year structure from future development as seen in Figure 3.11. Specifically, this flexibility arises from the possibility to account for (1) engineering-based technology information on input and cost structure, (2) discrete and different technologies with their specific characteristics at various points in time, (3) improvements of technology characteristics according to engineering knowledge and projections.

3.4.3 Economic and emissions results

One clear advantage of a CGE framework is the comprehensive coverage of CO₂ emissions on a national basis. In this study, CO₂ emissions are calculated at the point of emission, which is usually the point that fossil fuels are combusted. This presents an accounting difficulty for electricity because there are no emissions at the point the energy is consumed. This is important for the iron and steel sector as a significant amount of electricity is consumed but there are no direct CO₂ emissions where the electricity is used. A purchaser of electricity pays the average price across all generating options, and the appropriate amount of emissions to be charged is the average amount of CO₂ per kWh. However, the generating mix is changing over time and the average amount of CO₂ per kWh is also changing. Emissions calculations at the national level in a CGE model consider all of these interactions, but it would take some extra effort to reassign emissions from the electricity-generating sector to the various users of electricity. This section presents economy-wide results using a technology-based representation of steel production.

Results presented so far in this analysis were obtained by operating a CGE model for Germany at various CO₂ prices. However, the CO₂ prices were applied only to sectors covered by the EU CO₂ emissions trading program. As a point of comparison, we also ran the same CO₂ price scenarios, but with the entire economy exposed to a CO₂ price. As expected, national emissions reductions are greater with CO₂ prices applied to the entire economy. Figure 3.12 provides a time series of emissions projections from SGM-Germany for the following emissions scenarios: baseline (no CO₂ price); partial coverage at 20 Euros per t CO₂; partial coverage at 50 Euros per t CO₂; full coverage at 20 Euros per t CO₂; full coverage at 50 Euros per t CO₂. These scenarios are placed in context of various historical measures of CO₂ emissions in Germany and some future projections by others (DIW, 2004; Markewitz and Ziesing (M&Z 2004); Prognos/EWI, 1999; U.S. Energy Information Administration, 2002a; E3M Lab, 2003; and Esso, 2001).

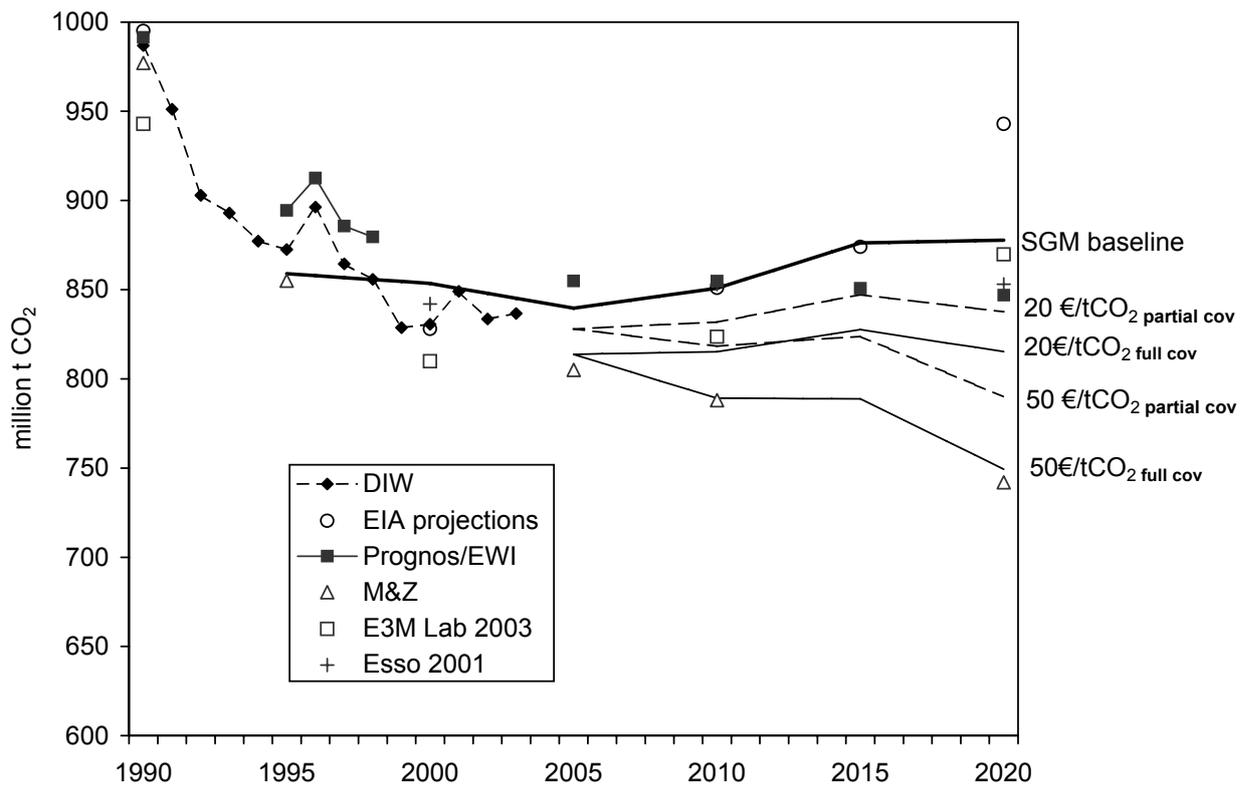


Figure 3.12 CO₂ emissions in Germany: historical and future projections from various sources

Figure 3.13 provides a breakdown of emissions reductions into broad groups of energy-consuming sectors at a CO₂ price of 50 Euros per t CO₂. CO₂ emissions from electricity generation are nearly the same between the partial- and full-coverage scenarios. In either scenario, emissions reductions increase over time due to the time it takes for existing capital stocks to turn over. Some of the reductions in emissions from electricity generation, especially in later years, are due to carbon dioxide capture and storage. Further background on the role of CO₂ capture and storage in SGM can be found in Schumacher and Sands (2006).

Manufacturing industries include energy-intensive and non-energy-intensive sectors. Thus, a difference in emissions reductions can be seen when a CO₂ price is only applied to the energy-intensive parts of manufacturing. Energy transformation sectors are included in the partial-coverage case, while services, transport and agriculture do not face a CO₂ price and thus do not contribute directly to emissions reductions.

The household sector provides an interesting comparison between full and partial coverage. Even though households are not included in the partial-coverage case, there is still a

reduction in emissions because the petroleum refining sector is covered and its price is higher in the partial-coverage case than in the base case.

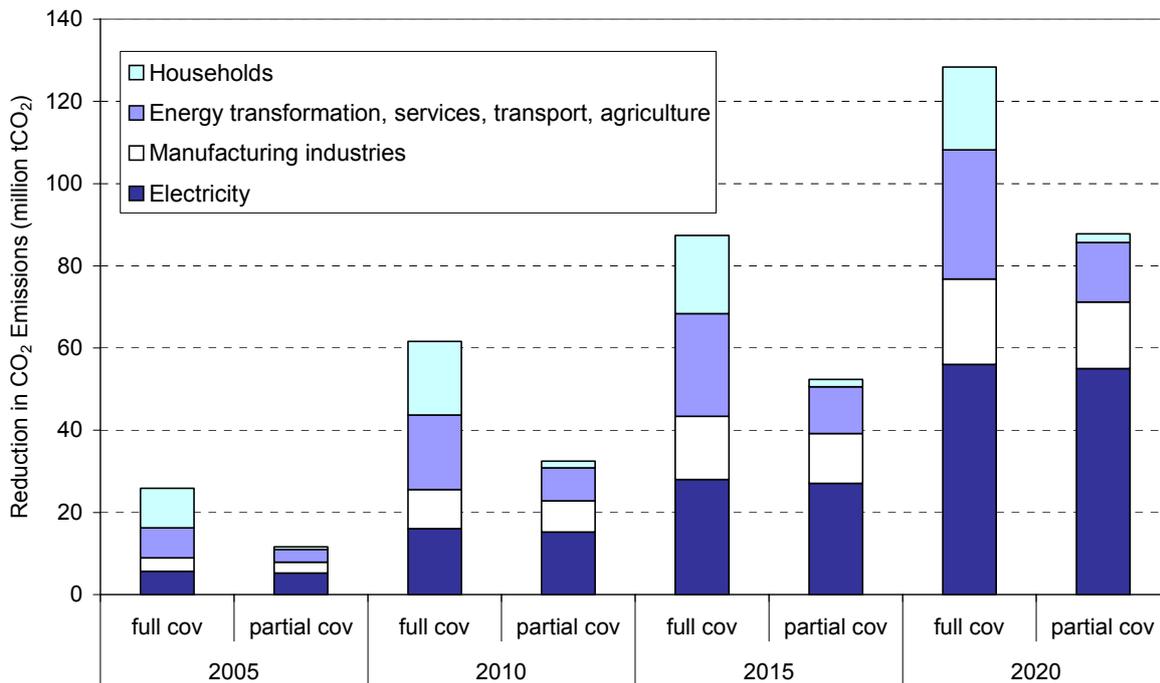


Figure 3.13 Decomposition of emissions reductions at 50€/t CO₂ across households and major types of industries.

3.5 Conclusions

Computable general equilibrium models have become a standard tool for analysis of economy-wide impacts of policy intervention (such as greenhouse gas abatement policies) on resource allocation and the associated implications for incomes of economic agents (Grubb et al., 1993). They provide a consistent framework for studying interactions between the energy system and the rest of the economy (Böhringer, 1998). For example, demand for energy-intensive goods will decline under a carbon policy because these goods become relatively more expensive. In some energy-intensive industries, especially electricity generation and steel production, response to an energy or climate policy occurs mainly through shifts between alternative production processes. This suggests that CGE models would benefit from including a representation of specific technologies. Our study demonstrates two important advantages of a technology-based approach: shifts in energy consumption are consistent with shifts between technologies, and the least-cost technology bounds the analysis.

This study explores a technology-based method for improving the realism of energy-intensive industries in a CGE model used for analysis of climate policy. Production sectors are commonly represented in CGE models by a CES cost function. However, industrial processes and technological change in these processes are generally not used to parameterize the CES cost function. Our technology-based approach replaces the CES cost function with a set of specific processes: each represents a specific technology with technical coefficients constructed from engineering data. We apply this approach to the iron and steel sector in Germany and account for five different production processes.

The study compares two ways of representing iron and steel production in a CGE model for Germany: a typical CES cost function approach, and a technology-based approach that allows shifts between distinct production processes. The study is designed to provide insights on the response of the iron and steel sector to a policy-induced price change, including changes in technological choice, in output, in the fuel mix and carbon emissions. Further, the integrated, technology-based, approach permits an analysis of interaction with other sectors, in particular the electricity sector and its efficiency, and their combined response to policy-induced price changes.

Our technology-based analysis reveals that CO₂ reductions in the iron and steel sector take place primarily due to process shifts towards less carbon-intensive production routes and due to output adjustments. It is important to model electricity and steel production together in a consistent framework because CO₂ emissions from an electric arc furnace, for example, depend on the mix of electricity generation processes, which itself will change with a climate policy. We also see that shifts in technology are not singular events but continue over time as new investment decisions are taken. Thus, policies induce long-term shifts in production capacities, technological change and carbon abatement.

A number of uncertainties affect the future development and selection of steel production routes. First, natural gas and scrap prices are more uncertain than coal prices, and we have conducted a limited sensitivity analysis. Higher natural gas and scrap prices lead to a decrease in the adoption of those technologies that use these factors intensively. Second, the timing of investment decisions depends on capacity utilization in the current capital stock. Implementation of new technologies can be delayed if the current stock of capital is running at less than full capacity. Third, we do not know how long existing plants will continue to operate. Retrofits and life extension could keep plants operating much longer than the 25 years we have assumed, and this limits opportunities for shifts to other production routes.

Fourth, future technical change is not easy to predict. But we do have an understanding of the difference between average practice and best practice.

This study demonstrates that it is constructive and feasible to operate CGE models at an intermediate level of technology detail. The extra effort to collect engineering cost and performance data, and to reconfigure a benchmark data set to accommodate these data, can be justified as it improves the realism of policy simulations.

This type of analysis can be extended to other energy-intensive industries and to other countries. Ultimately, we would like to compare results between countries, especially between developed and developing countries. A technology-based approach may help address questions about relative costs of producing steel between countries and how that might change when one country faces carbon constraints but another does not. Further model development could also include endogenous adjustment of technological characteristics, such as through learning-by-doing or R&D investment.

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4 Economic comparison of GHG mitigation strategies²⁴

4.1 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 (CO₂). These options vary by cost, timing, and our ability to represent them in an economic analysis. Our objective in this study 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-CO₂ 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, CO₂ prices, fuel prices, and baseline energy consumption. We use the CGE model as a core to provide analysis of the energy efficiency, fuel switching, and CCS mitigation options. Analysis of the non-CO₂ 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. Allowing for a reduction of emissions of non-CO₂ 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

²⁴ This work will be presented at the 10th annual conference “Assessing the foundations of global economic analysis” of the Global Trade Analysis Project (GTAP) at Purdue University and at the International Energy

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 CO₂ price or change in fuel price.

There are two parts to our analysis of non-CO₂ greenhouse gases for Germany: first we determine baseline emissions 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 CO₂-equivalent price. The marginal abatement cost curves determine a percentage reduction in greenhouse gas emissions, relative to the baseline, for any given CO₂-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-CO₂ greenhouse gas mitigation options. Mitigation policies are represented with a set of constant-CO₂-price experiments covering a range of CO₂-equivalent prices high enough so that CCS technologies can at least break even.

Section 4.2 provides a brief overview of historical and current greenhouse gas emissions and reduction efforts in Germany. We introduce the SGM model in section 4.3 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 4.4, 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 4.5 summarizes the results and provides some conclusions.

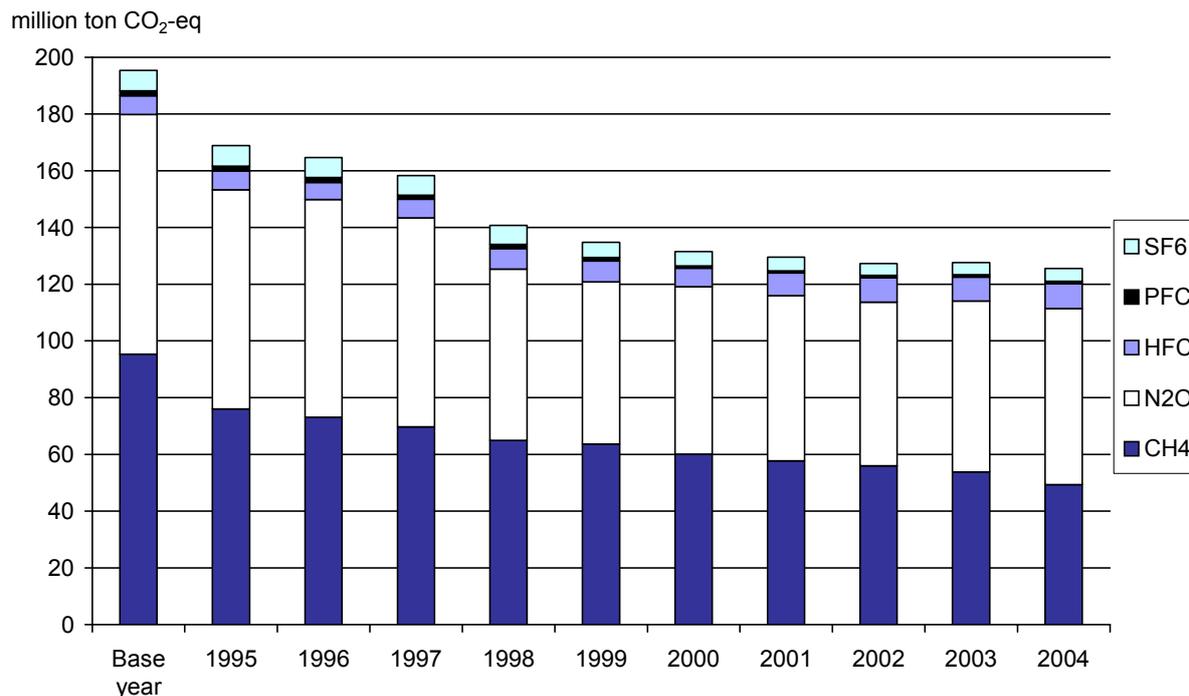
4.2 Background

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 2004, Germany emitted greenhouse gases of about 1009 million t CO₂-equivalent (DIW, 2006). CO₂ emissions accounted for the major share (87.6%) of overall greenhouse gas emissions in Germany, while non-CO₂ greenhouse gases amounted to 12.4% of total greenhouse gas emissions. Compared to the base year²⁵, 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.

Greenhouse gas emissions originate from many different sources. While CO₂ emissions can be linked to fossil fuel use, in particular the combustion of fossil fuels and, to a lesser extent, fossil fuel use related industrial process emissions, non-CO₂ emissions emanate from activities that are not necessarily related to fossil fuel use. CH₄ 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, N₂O emanates from fertilizer use and selected natural resources, as well as combustion processes, to a large share transport related, and industrial processes. SF₆ stems from electrical switchgear and other industrial processes, and emissions of F-gases result from purely industrial processing with no link to fossil fuel use.

In Germany, nitrous oxide (N₂O) and methane (CH₄) account for the largest shares of non-CO₂ greenhouse gases, followed by HFCs. From 1990 to 2004, N₂O and CH₄ emissions have been declining (Figure 4.1). For CH₄, 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).

²⁵ The base year is 1990 for CO₂, CH₄ and N₂O emissions and 1995 for emissions of F-gases (HFC, PFC, SF₆).



Note: Base year 1990 for CH₄ and N₂O, 1995 for PFC, HFC and SF₆. Source: DIW (2006)

Figure 4.1 Non-CO₂ greenhouse gas emissions in Germany, 1995-2004

For N₂O, 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 N₂O 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). SF₆ emissions have undergone only slight changes in the last decade (NC3, 2002).

4.3 Methods

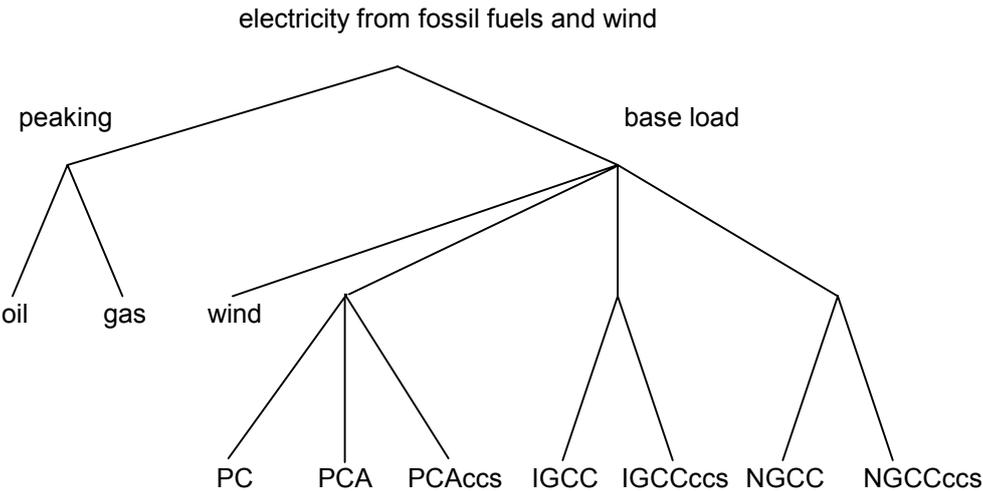
4.3.1 SGM-Germany

We employ the same computable general equilibrium model as in the previous two chapters, the Second Generation Model (SGM), to conduct an 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. For a detailed description of the model, its main features, assumptions, set up and restrictions, for references, and information on data used please see chapter 2.3.

The electricity sector nesting differs slightly from the one introduced in chapter 2.3. As in chapter 3, we include an additional coal technology that represents an advanced version of conventional pulverized coal power production (PCA). The same technology can be implemented with or without the option of CO₂ capture and storage. We included an advanced pulverized coal version to allow oxyfuel and post-combustion CO₂ capture and storage to compete with other electricity technologies.

Figure 4.2 provides the nested logit structure of electricity technologies employed in this chapter. 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 CO₂ price is introduced, the levelized cost per kWh increases for all generating technologies that emit CO₂. Technologies that are less carbon intensive receive a larger share of new investment than before the CO₂ price was introduced.



Note: PC refers to conventional and PCA to advanced pulverized coal electricity generation. “PCAaccs” represents advanced pulverized coal with CO₂ capture and storage, “IGCCccs” represents coal IGCC with CO₂ capture and storage, and “NGCCccs” represents NGCC with CO₂ capture and storage. .

Figure 4.2 Nested logit structure of electric generating technologies in SGM-Germany

4.3.2 Greenhouse gas emissions

Emissions of non-CO₂ greenhouse gases are calculated differently than emissions of CO₂, which emanate from the burning of fossil fuels and are considered to be 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 sectoral 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 CO₂ emissions. Non-CO₂ emissions, however, are not limited to fuel use activities. Therefore, emissions of those gases require a different tracking procedure. Table 4.1 shows the greenhouse gases and their sources that are included in our analysis.

Table 4.1 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 ₂ O | 8 | Agricultural soil |
| | 9 | Industrial processes |
| | 10 | Manure |
| | 11 | Fossil fuels |
| | 12 | Waste |
| HFCs | 13 | Solvent use and other product use |
| | 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 CO₂ emissions from 1995 up to 2050, for both baseline and mitigation scenarios. Reductions in CO₂ emissions are obtained by operating SGM-Germany at various CO₂ price paths. Several advanced electricity generation options are available, including carbon dioxide capture and storage.

For the baseline scenario of non-CO₂ greenhouse gas emissions we rely on exogenous information and projections of DIW (2006), Diekmann et al. (2005), UBA (2005), NC3

(2002), Prognos/EWI (1999) for emissions of non-CO₂ greenhouse gases from different sources. In the mitigation scenarios, reductions in emissions of the non-CO₂ 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 CO₂ 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 (CH₄), coal mining (CH₄), natural gas production and distribution (CH₄), solid waste management (CH₄), agricultural soils (N₂O), and production of adipic and nitric acid (N₂O). In addition, marginal abatement cost curves were provided for three types of F-gases: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF₆).

4.4 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 CO₂ policy scenario that includes a stepwise CO₂ price increase from 10 € per ton of CO₂-eq in 2005, to 20 € per ton of CO₂ in 2010 and continues to increase to 50 € per ton of CO₂-eq in 2025; we also conduct five constant-price scenarios at 10, 20, 30, 40 and 50 € per ton of CO₂-eq starting in 2005. For the latter four scenarios, the CO₂-equivalent price is introduced in 2005 at 10 € per ton of CO₂-eq and increased to 20, 30, 40 and 50 € respectively by 2010 (compare Table 4.2). In the first set of results, referred to as

partial coverage, CO₂ 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 CO₂ 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 CO₂ 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 4.2 Greenhouse gas price scenarios. All scenarios reach a maximum CO₂-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 |

4.4.1 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 CO₂ capture and storage technologies in a base case and under different assumptions about a CO₂ price.

Figure 4.3 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. 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 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.

CO₂ 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 CO₂ 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 CO₂ prices but old capital does not. Therefore, the full impact of a CO₂ price is delayed until all old capital retires.

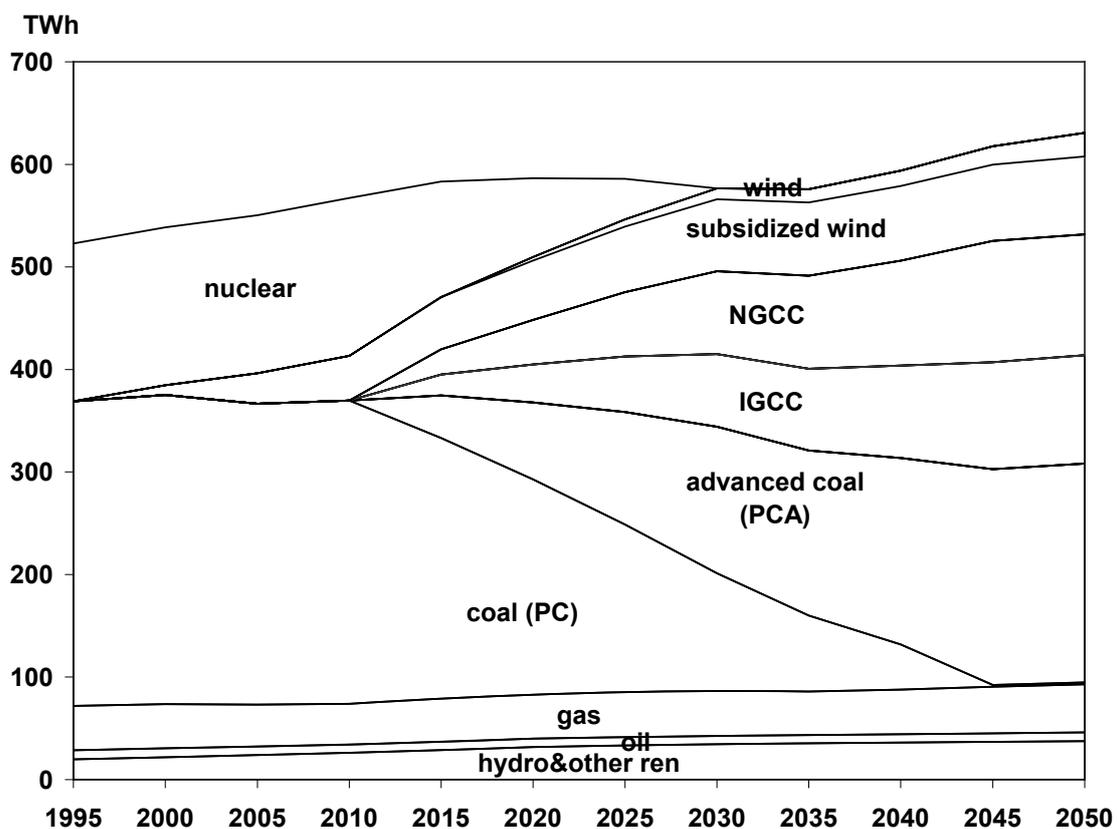


Figure 4.3 Baseline electricity generation in TWh

The climate policy scenario consists of a stepwise CO₂ price increase (compare Table 4.2). As shown in Figure 4.4, total electricity generation is lower in the climate policy scenario than in the baseline. The impact of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ prices, energy technologies that are less carbon-intensive (renewable technologies, CO₂ capture and storage for fossil fuel based technologies) increase their share of electricity generation. At lower levels of CO₂ prices (20 to 50 € per t CO₂), CO₂ capture and storage technologies as well as advanced wind still come into place, but with a reduced share of generation.

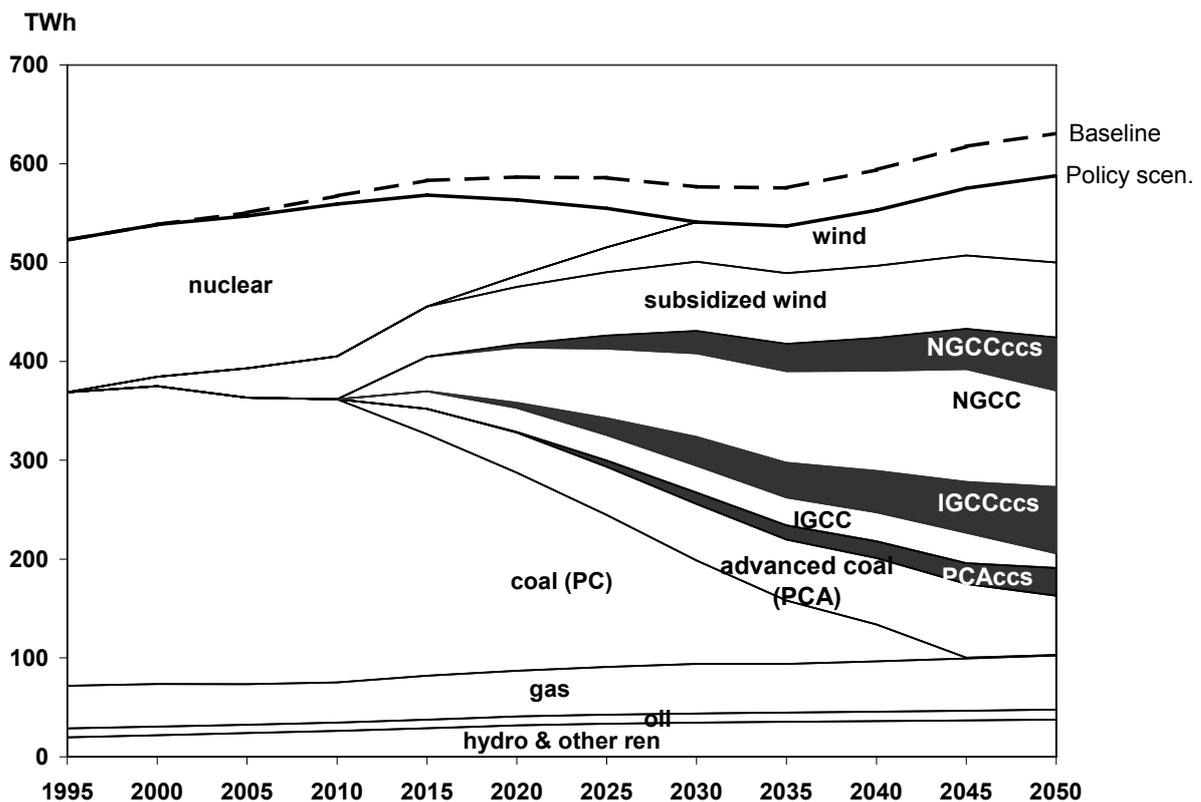


Figure 4.4 Electricity generation mix with a stepwise CO₂ price increase

4.4.2 Results for greenhouse gas emissions

Baseline projections for CO₂ (from SGM) and the non-CO₂ greenhouse gases (from German data sources) are shown in Figure 4.5. Baseline emissions of CO₂ resulting from

fossil fuel use decline in accordance with past data until 2005 and slowly rise again thereafter. Emissions of non-CO₂ gases show a future pattern consistent with past trends (compare section 4.2). CH₄ emissions continue to fall rapidly until 2010 and then gradually decline; N₂O 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-CO₂ gases are not available after 2030; therefore, baseline levels of non-CO₂ gases are held constant after 2030. Emissions of non-CO₂ greenhouse gases are weighted at their 100-year global warming potential. All results are expressed as annual emissions in metric tons of CO₂-equivalent, through the year 2050.

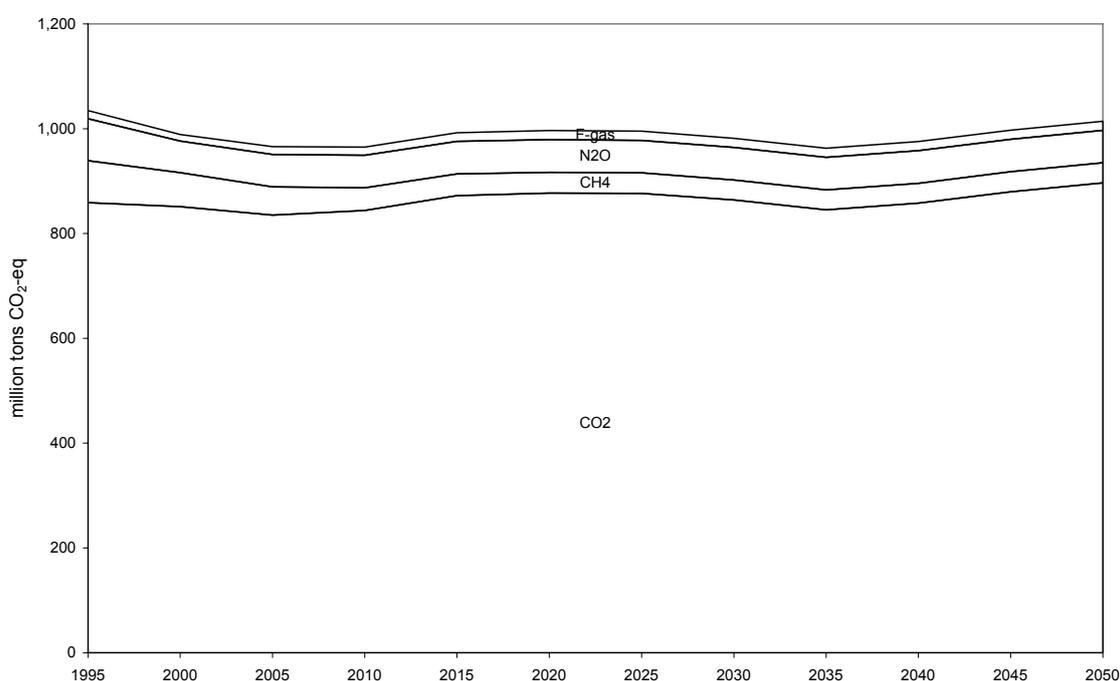


Figure 4.5 Greenhouse gas emissions pathway, baseline

Figure 4.6 and Figure 4.7 show simulated greenhouse gas emissions at CO₂-eq price scenarios of 20 € and 50 € respectively, targeted to those sectors that are covered under the EU emissions trading scheme. CO₂ prices follow the time paths shown in Table 5.1. Reductions in CO₂ 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 CO₂ prices. By 2020, a 50 € price yields a 10% reduction of CO₂ emissions, which doubles to more than 20% by 2040.

Reductions in greenhouse gas emissions other than CO₂, however, are less sensitive to a CO₂-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 .²⁶ 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 €.

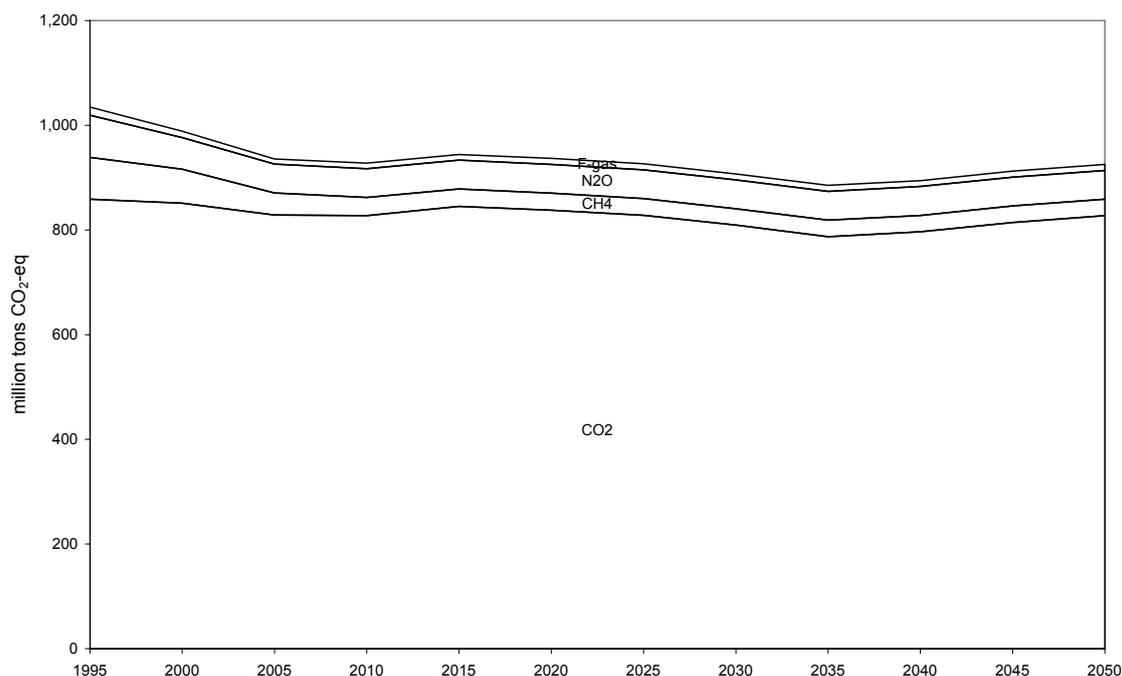


Figure 4.6 Greenhouse gas emissions pathway, 20 € per ton CO_2 -eq

²⁶ 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.

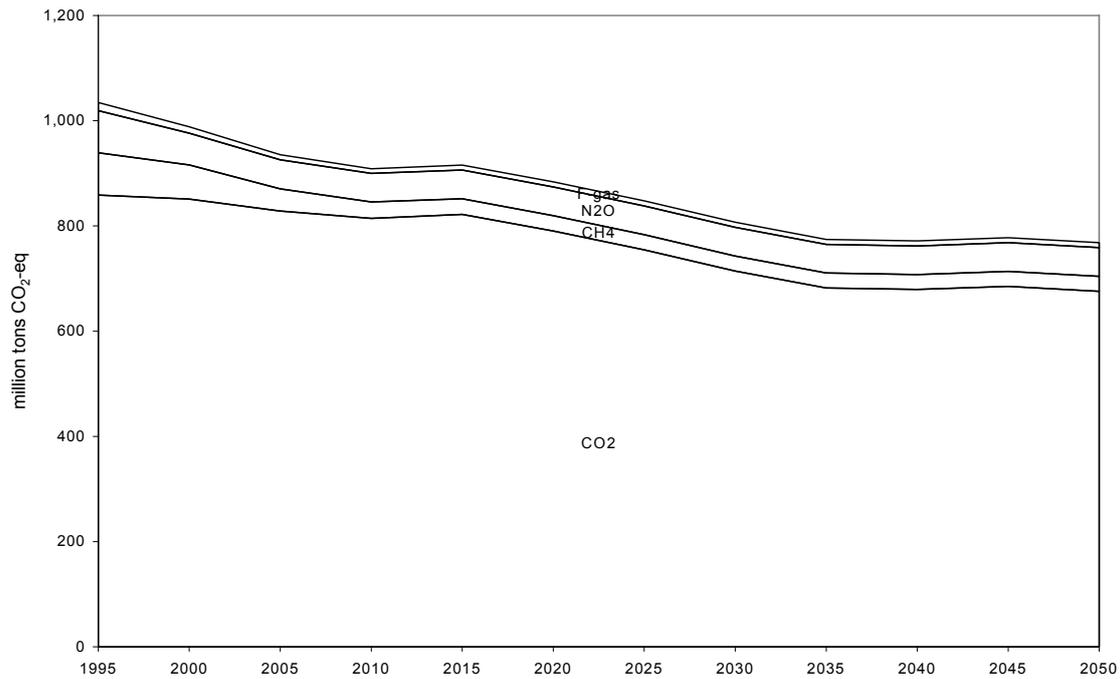


Figure 4.7 Greenhouse gas emissions pathway, 50 € per ton CO₂-eq

4.4.3 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 4.8 and Figure 4.9 for two different time periods (2020 and 2040) with four separate components: efficiency improvements outside of electricity generation; efficiency improvements and fuel switching within electricity generation; CCS within electricity generation; and reductions in emissions of non-CO₂ 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 CO₂ prices.

For each of the four components, we derive its contribution to the overall marginal abatement cost curve by conducting a set of CO₂-eq price scenarios and determining the reduction in emissions relative to the baseline. The component of non-CO₂ greenhouse gas emissions reductions is calculated based on exogenous information as described in the previous section. For the CCS component, we operate SGM-Germany with and without the option of CCS and allocate the difference in electricity sector emissions to CCS-related emissions reductions. The fuel switching component is derived by comparing electricity-sector emissions for each CO₂ price scenario with a calculation assuming fuel shares remain at baseline levels, adjusting for output changes in electricity generation. Residual emissions

reductions are then considered to be due to efficiency improvement in the economy. The outer lines in Figure 4.8 and Figure 4.9 encompass all these options and provide economy-wide marginal abatement cost curves.

Although we generated these sets of marginal abatement cost curves with a number of constant CO₂-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 (CO₂ price) and the set of mitigation options employed.

As can be seen for the year 2020 in Figure 4.8 and even more pronounced for the year 2040 in Figure 4.9, the efficiency and fuel switching components increase gradually along with time and with the CO₂ price and they have large potential at high CO₂ prices. The efficiency component captures shifts in consumption by both producers and consumers: they substitute other goods for energy in consumption and production as the CO₂ price rises. Substitution elasticities in production and consumer demand elasticities are the key parameters that govern the price response. The label 'fuel switching' in the figures relates to emissions reductions in the electricity sector resulting from fuel switching as well as efficiency improvement in electricity generation, with fuel switching taking on the substantially larger share of emissions reductions (compare Figure 4.4). The mix of electricity generating technologies changes in response to a CO₂ price. As the CO₂ 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.

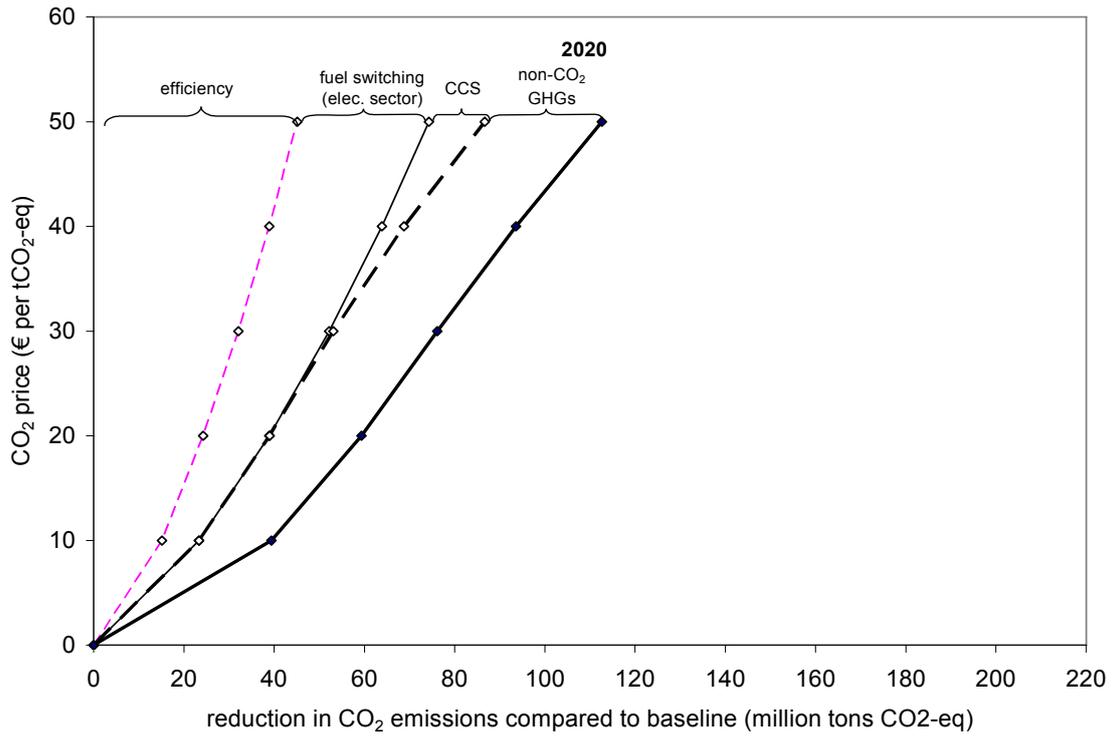


Figure 4.8 Simulated emissions reductions over a range of CO₂ prices, Germany 2020

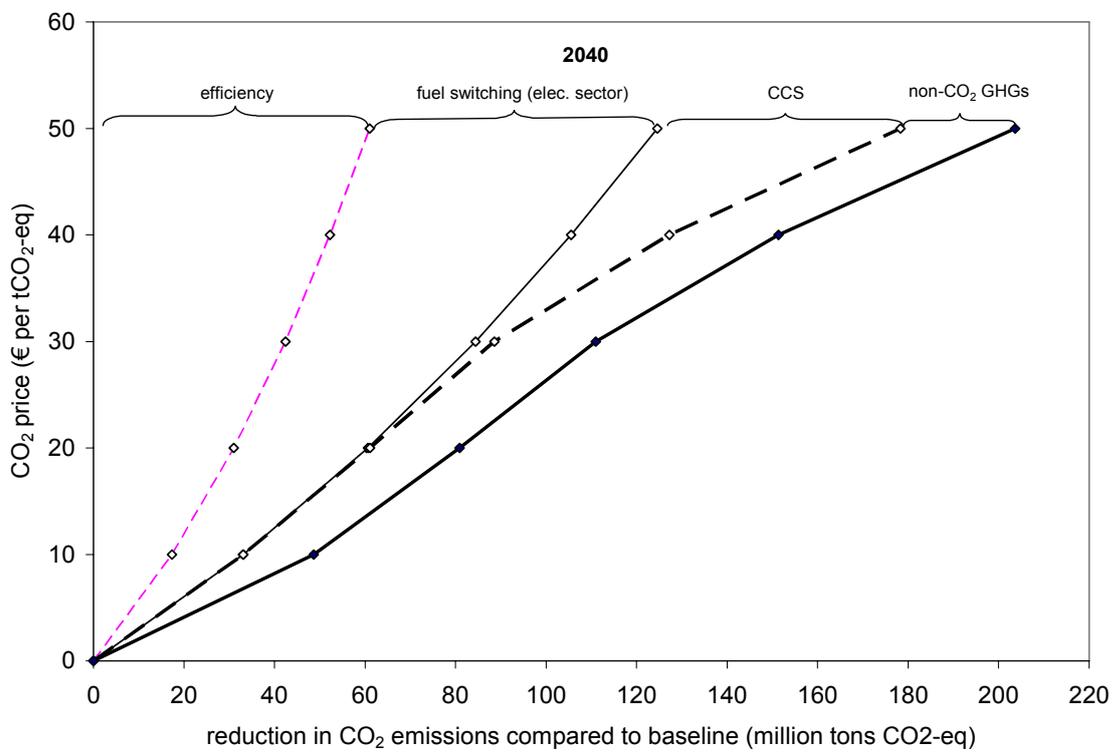


Figure 4.9 Simulated emissions reductions over a range of CO₂ prices, Germany 2040

In addition, CCS is introduced as a mitigation option in the electricity sector. CCS is not available at low CO₂ prices, but can be a significant contributor to emissions reduction at CO₂ prices above 30 € per ton. For each electricity generating technology that can use CCS, one can calculate a break-even CO₂ price where the cost per kWh of generating electricity is the same with or without CCS. At this CO₂ 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. This can be seen by comparing the contribution of CCS to CO₂ mitigation over time at relatively high CO₂ prices. Figure 4.9 shows the higher mitigation potential of CCS in 2040 compared to 2020. A similar, but not quite as pronounced, case can be made for energy efficiency and fuel switching. Over time, both of these options experience an increasing economic potential and can, by 2040 and at a high 50 € per ton of CO₂ price, contribute to emissions reductions at almost equal shares with CCS.

The non-CO₂ greenhouse gases reach most of their full mitigation potential at low CO₂ prices. This is a consequence of using exogenous marginal abatement cost curves and simplifying assumptions on the requirements for new capital. The non-CO₂ 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.

To summarize, the analysis shows that all four mitigation options (efficiency increase, fuel switching, CCS, and GHG mitigation) respond to a CO₂ price policy with varying degrees of sensitivity. Initially, non CO₂-GHG mitigation and energy efficiency improvement on the producer and consumer side play the dominant role in achieving emissions reductions in response to a CO₂ price. An increase in energy efficiency is stimulated already at low levels of CO₂ 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 CO₂ price an increasing share is taken up by fuel switching, mainly driven by changes in the electricity generation mix as outlined above. Similarly, the introduction of CCS technologies in the electricity sector after 2015 plays a major role. At a CO₂ price of 50 € per ton of CO₂ (year 2025) CCS is economically competitive and takes on an increasing share as capital stocks turn over.

4.4.4 From partial to full coverage of economy

In the second set of results, referred to as full coverage, CO₂ incentives are applied to all sectors of the economy. We apply the same CO₂ price scenarios as above, i.e. a price of 10, 20, 30, 40 and 50 € per ton of CO₂-eq. The CO₂ price is introduced in 2005 at 10 € per ton of CO₂-eq and increased to 20, 30, 40 and 50 € respectively by 2010. .

As now all sectors of the economy are exposed to the CO₂ price scheme, the resulting aggregate CO₂-eq emissions reductions are much higher than in the partial coverage case. Figure 4.10 shows the distribution of emissions reductions across different mitigation classes for the two cases in a scenario with a stepwise CO₂ price increase. The deviation from baseline increases over time as old capital is retired. The largest difference between the full and the partial coverage case can be seen in emissions reductions that result from energy efficiency improvement. This is because in the partial coverage case carbon incentives are only targeted to a limited set of sectors, i.e. electricity and energy intensive industries. These sectors, however, are mainly responsible for emissions reductions through fuel switching and introduction of CCS and only to a lower extent through efficiency improvement.

The remaining sectors, such as non-energy intensive manufacturing, services, transport, agriculture, and, in particular, the household sector, adjust their behavior through either efficiency improvement or output changes. In the full coverage case they face a direct CO₂ price and directly contribute to emissions reductions. In addition, they experience indirect price increases, for example in electricity prices or refined petroleum price and adjust their behavior accordingly. In the partial coverage case they are not directly covered by the CO₂ price scheme and only the indirect price effect applies. Therefore the impact on efficiency improvement and emissions reduction is much smaller than in a full coverage case.

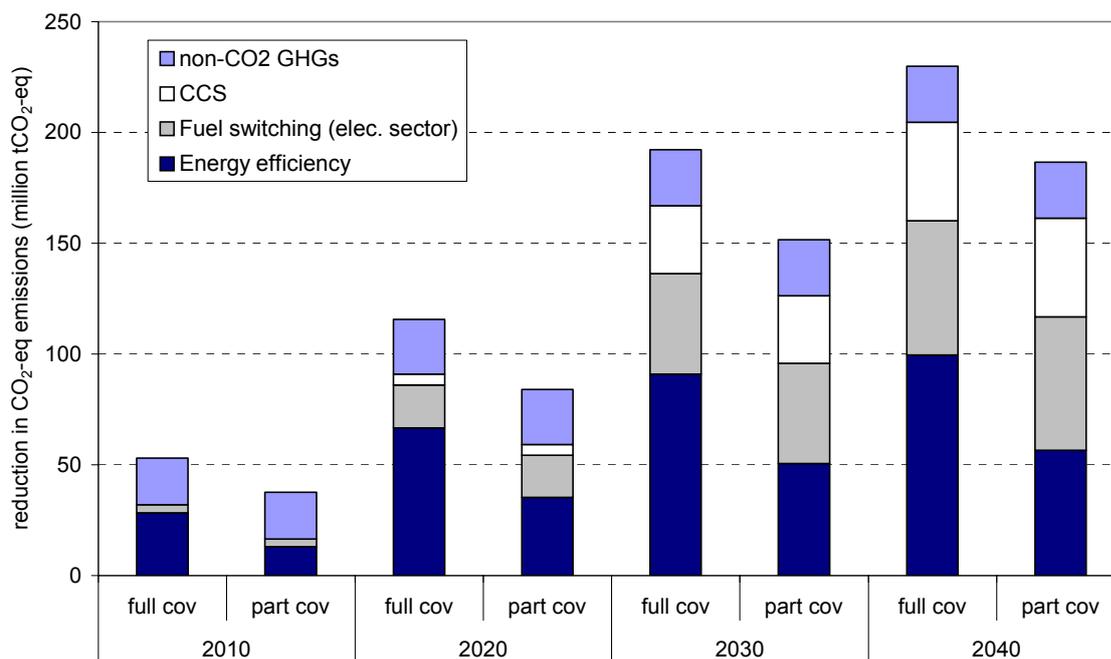


Figure 4.10 Decomposition of emissions reduction with a stepwise increasing CO₂ price fully and partially covering the economy

The energy efficiency component includes both changes in the ways that producers use energy but also shifts in output across production sectors as consumers adjust purchases to a new CO₂ price. Output of the energy-intensive industries and electricity generation decreases more than output of other sectors of the economy, as energy costs are a larger share of the cost of production. Even the very large “services and other industries” sector, which has a low energy cost share, shows a small decrease in output, reflecting the GDP loss of the CO₂ price increase.

Quantity changes of gross output by sector aggregate in relation to the baseline are shown in Figure 4.11 for the 50 € per t CO₂ scenario applied to all sectors of the economy (full coverage) and in Figure 4.12 for the 50 € per t CO₂ scenario applied to parts of the economy (partial coverage). 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 CO₂ price and lower overall emissions reduction is achieved. This turns out to be approximately the same as

the percentage loss in real GDP²⁷. Other sectors are much smaller in terms of output, but are more sensitive to the CO₂ 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% in both cases, yet it is slightly lower in the partial coverage case as only energy-intensive manufacturing sectors are covered by the CO₂ price scheme. The most pronounced difference between the full and the partial coverage case can be seen in the energy transformation (most oil refining) and transportation sector. Output losses for transportation sector are substantially lower in the partial coverage case, when not affected by a CO₂ price. Consequently, a reduced loss in output from energy transformation can be observed as demand for petroleum products by the transport sector spurs production.

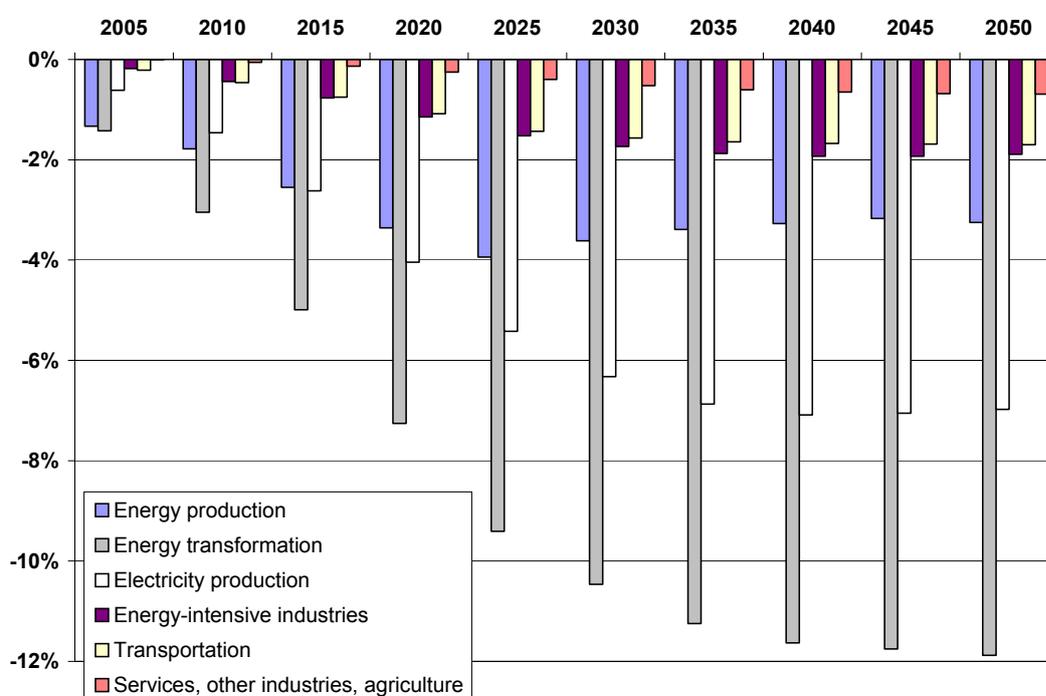


Figure 4.11 Change in sectoral output, stepwise CO₂ price applied to all sectors of the economy (full coverage), compared to baseline

²⁷ 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.

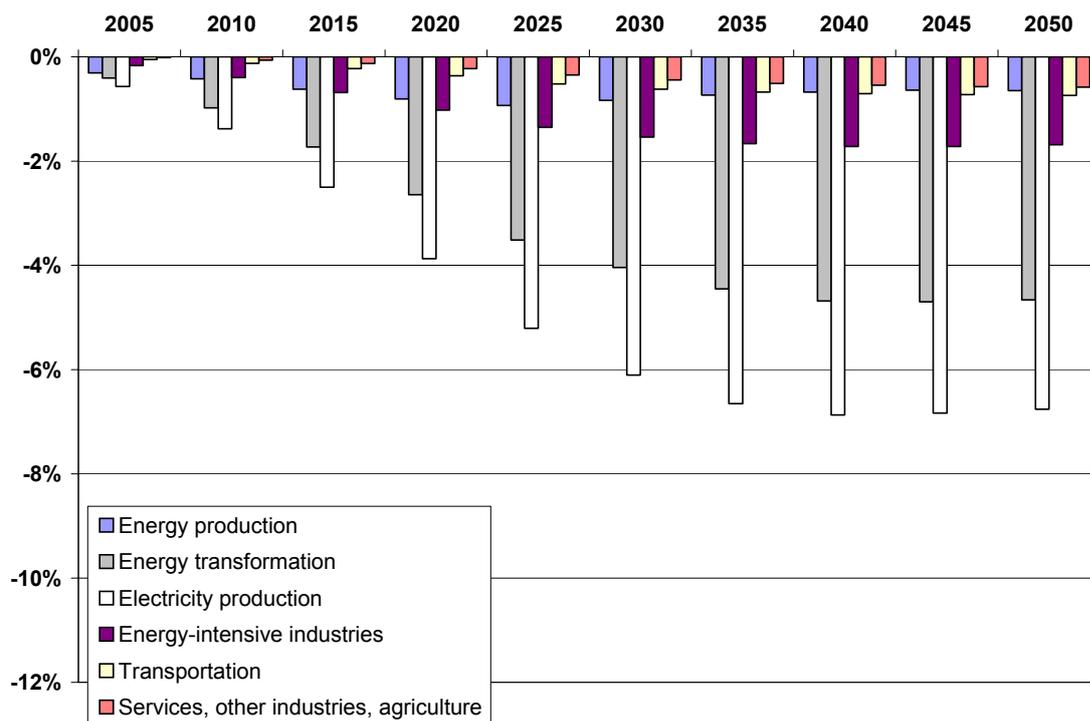


Figure 4.12 Change in sectoral output, stepwise CO₂ price increase applied to parts of the economy (partial coverage) compared to baseline

4.5 Conclusions

This study builds on previous analysis by Schumacher and Sands (2006), where the primary extensions here are the inclusion of non-CO₂ greenhouse gases and a broader set of climate policies. The non-CO₂ 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-CO₂ 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 CO₂ price applied to all sectors of the economy, and another with the CO₂ 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 switch 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 efficiency component into production efficiency and output shift components. Currently, the energy efficiency component includes both changes in the ways that producers use energy but also shifts in output across production sectors as consumers adjust purchases to a new CO₂ price. Decomposing the energy efficiency component would allow to distinguish 'pure' efficiency effects from output effects. Output effects 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-CO₂ 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 CO₂ prices.

4.6 References

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5 Learning-by-doing in renewable energy technologies²⁸

5.1 Introduction

In economic models of energy or climate policy, endogenous technological change is generally modeled as the result of investment in research and development (R&D) or of learning-by-doing (LBD). Both channels are based on the idea that there is a stock of "knowledge", which accumulates in reaction to an economic activity such as production or R&D. This knowledge influences production possibilities (or sometimes also consumption). In the first case (R&D), a stock of knowledge or human capital is generated through investment into research and development activities. Model parameters, such as price changes induced by policy measures, may lead to increased investment into the stock of knowledge capital with its subsequent effects on production possibilities and productivity. In the second case (LBD), knowledge accumulation is based on experience in producing or using a specific technology or process. The application of specific technologies, which may be encouraged by policy measures or other model parameters, then results in a decline of production costs as experience with this technology accumulates.

Given the model structure and sectoral and technology detail, macroeconomic (top-down) modelers tend to focus on the R&D approach while the majority of engineering (bottom-up) modelers focus on implementing the LBD approach taking advantage of the technological detail inherent to these models. For an overview of modeling approaches and results see, for example, Vollebergh and Kemfert (2005), Jaffe et al. (2003), Löschel (2002), Grübler et al. (2002), Edmonds et al. (2001).

Few studies so far have implemented learning effects into macroeconomic (top-down) models. They mainly differ with respect to the proxy/indicator for the activity which causes learning: i) cumulative installed capacity of a technology (Gerlagh and van der Zwaan, 2003), ii) sectoral output (Rasmussen, 2001; Carraro and Galeotti, 1997), iii) sectoral capital stock (van Bergeijk et al., 1997), iv) sectoral labor input (Kverndokk et al., 2004), v) technological know-how (learning-by-researching) (Goulder and Mathai, 2000), or vi) a combination of these indicators such as the two-factor learning curve that takes into account cumulative

²⁸ This paper has been submitted for publication to the Energy Journal (co-authored by M. Kohlhaas).

capacity as well as cumulative R&D expenditure (Kouvaritakis et al., 2000; Klaassen et al., 2005).

Most studies agree that learning effects are most pronounced for relatively new technologies, e.g. non-fossil energy technologies. Thus, they separate fossil energy from non-fossil energy and analyze the effects of learning-by-doing in non-fossil energy goods, such as renewable energy. When technological progress is induced via learning-by-doing rather than by autonomous efficiency improvement, this may have an influence on the optimal timing of environmental policies and of investment, which is the focus of most of those studies.

Conventionally, learning-by-doing effects in the renewable energy sector are allocated to the production of renewable based electricity. In this study, we build on the observation that learning-by-doing also takes place in sectors that deliver capital (investment) goods to the renewable electricity sector, such as the production of machinery and equipment for renewable energy technologies. Machinery and equipment components have substantially improved over time leading to lower unit capital costs. Such improvements for wind power, for example, include increased hub height, larger rotor blades, innovative technologies such as new direct-drive (gearless) systems, better foundation and site preparation and more (Neij et al., 2004). Thus, substantial learning effects have been induced by both increasing experience in producing renewable energy technologies and using it to produce electricity. Naturally, there are additional learning effects on the electricity production side. They include an improvement in identifying and making use of most favorable locations, better information technology to respond to changing conditions.

In this study, we introduce learning-by-doing on a sectoral basis in an energy-economy top-down general equilibrium model. LEAN_2000 is a two-region empirical general equilibrium model for Germany and the rest of the European Union with a particular emphasis on the representation of the energy markets and the simulation of policies to reduce CO₂ emissions (Welsch, 1996). We implement learning-by-doing in both the renewable energy equipment industry and in renewable electricity production and show why it matters to differentiate between these two approaches. The main differences originate from the impact on international trade. This is due to the fact that the output of the machinery and equipment sector is intensively traded on international markets unlike renewable electricity.

Learning is modeled as a function of the cumulative output in a sector and increases the efficiency of new technologies. This means that any given output can be produced at reduced costs because of increased efficiency in the use of, for example, capital and labor. We expect

two main effects to take place by introducing learning-by-doing in the renewable energy equipment industry. Firstly, learning-by-doing leads to a reduction of the unit costs of equipment, which will via capital goods (investment) further translate into reduced renewable electricity costs and prices. The second effect relates to international trade. Renewable energy technologies are produced for either domestic demand or for exports. Exports in the sector are non-negligible (DEWI, 2006) and may even be more important in the future. In the case of wind power, for example, (on-shore) locations are getting scarce in Germany on the one hand, and on the other hand, world markets for wind are likely to be growing. Taking account of exports of renewable energy technologies may lead to a higher total demand for renewable energy equipment and result in higher learning effects with its subsequent effects on costs and prices. This increases the international competitiveness of renewable energy equipment and stimulates national and international demand for this technology, which then again would induce higher learning (first-mover advantage). An analysis of learning-by-doing effects in the production of renewable electricity alone is not able to take account of these international trade effects.

In addition to international trade of a specific good, such as renewable energy equipment, knowledge and technical know-how about this good, which is responsible for learning processes, can spill over from one country to another. Such knowledge spillovers and the induced innovation and diffusion of new technologies have been intensively discussed in the context of climate policy modelling (for an overview see Sijm, 2004 or Weyant and Olavson, 1999). A spillover can be defined as ‘any positive externality that results from purposeful investment in technological innovation or development’ (Weyant and Olavson, 1999). In view of German renewable energy equipment, spillover effects can take place in several ways. For one, Germany can profit from knowledge accumulated outside of Germany. Reversely, knowledge gained in Germany spills over to other countries. Moreover, several regions can simultaneously accumulate experience based on combined efforts to produce a technology. Depending on how such spillover effects are treated substantial effects on domestic production and exports patterns can be observed. Our analysis reveals positive effect of learning-by-doing on export opportunities and domestic production in Germany.

The remainder of this study is organized as follows. Section 5.2 provides a brief overview of the current status of the renewable energy industries in Germany. Section 5.3 discusses methodological issues related to the concept of learning-by-doing, while section 5.4 describes the CGE model employed (LEAN_2000) and the implementation of learning-by-

doing in the model. The scenario analysis and results including a sensitivity analysis of spillover effects are presented in section 5.5. Section 5.6 summarizes the main findings and gives suggestions for future modeling strategies.

5.2 Renewable energy in Germany

Renewable based electricity generation has increased substantially in Germany over the last decade. Between 1994 and 2004, installed renewable electricity capacity quadrupled from about 6 GW to 24 GW (BMU, 2005). The increase can be attributed almost entirely to a soaring growth of wind power capacity (Figure 5.1).²⁹ In 2004, 9.4% of German electricity supply was generated by renewable energy sources (BMU, 2005). The German government aims to increase the share of renewable based electricity production by the year 2010 up to at least 12.5%. In the medium term, the goal is to produce at least 20% of electricity from renewable energy by 2020. In the long term, by 2050, the goal is to see the renewable share rise to at least 50% of total electricity production.

A renewable energy law was introduced to help reach these goals. The law was originally passed in 2000 and replaced the electric power feed-in-law of 1991. The law supports renewable energies (wind power, hydropower, solar energy, biomass) through two main features: a fixed compensation for renewable-based power fed into the grid, and a priority purchase requirement for renewable power imposed upon transmission system operators.

²⁹ Because wind power is the main driving factor of renewable electricity growth, the focus of this paper is on wind power production. Although the analysis refers to renewable electricity generation in general, many examples and explanations will relate to wind power production.

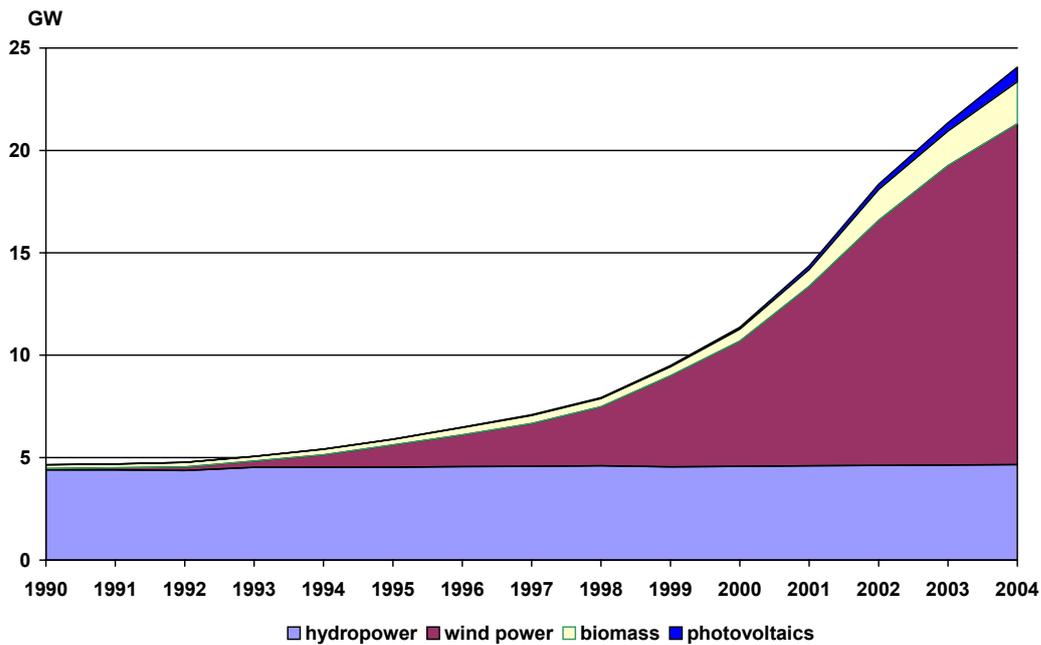


Figure 5.1 Installed renewable electricity capacity in Germany

Compared to other EU countries, Germany has by far the largest installed capacity of wind power, followed by Spain, Denmark and the Netherlands. While in 1997 Germany and Denmark had roughly the same total installed capacity of 2 GW, installed capacity in Germany had grown to more than 16 GW by 2004, whereas Denmark stagnated at about 3 GW (Figure 5.2).³⁰ In the early years of wind power generation (1995), most of the wind turbines were manufactured in Denmark and exported to Germany and other countries. The supply of wind turbines in Germany, however, is now mostly domestic (60%) (Neij et al., 2004). Moreover, exports of wind turbines from Germany have grown rapidly from a capacity of about 18 MW in 1994 to roughly 750 MW in 2003 (DEWI, various years). In 2004, Germany exported about 50% of its total domestic wind turbine production, mainly to Egypt, Japan, Austria, Australia and Slovakia (VDMA, 2005). This equals the average export share of the German manufacturing sector.

With respect to costs of producing wind power, capital costs capture the highest share. The wind turbine itself accounts for about 80% of total costs. Additional costs relate to the installation of the wind turbine, such as costs of foundation, installation work, site

³⁰ Denmark, however, still possesses a higher share of wind power in total electricity generation. About 20% of electricity was supplied by wind energy in Denmark in 2004. In contrast, the share in Germany amounts to only about 6%.

preparation, roads, grid connection and also operation and maintenance work (Neij et al., 2004).

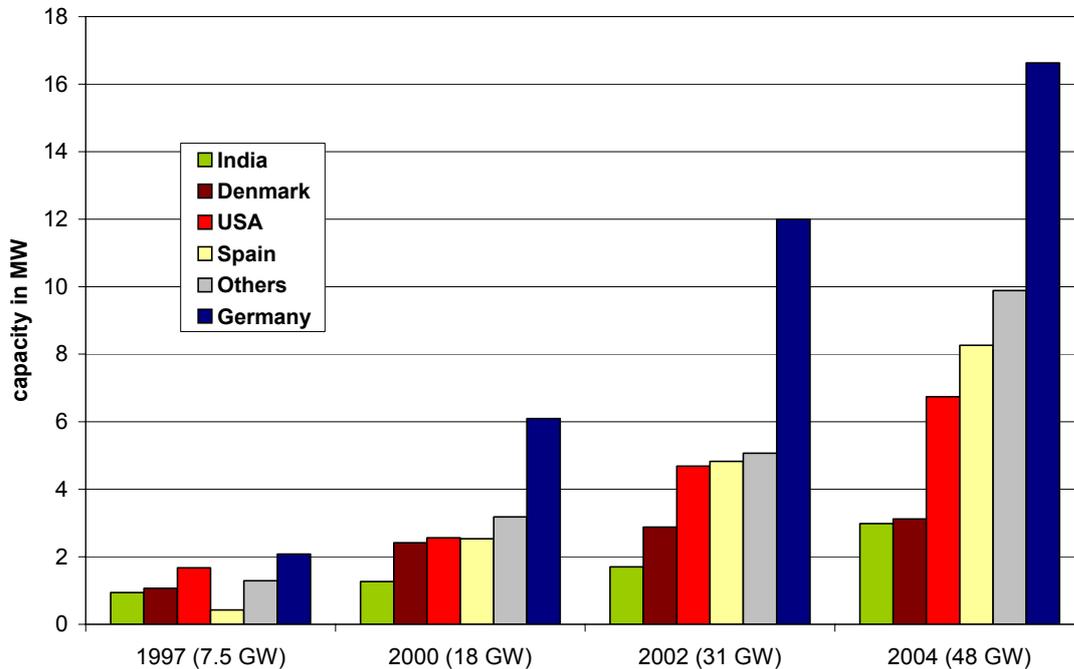


Figure 5.2 Total installed capacity of wind power, 1997-2004

5.3 Learning-by-doing and renewable energy

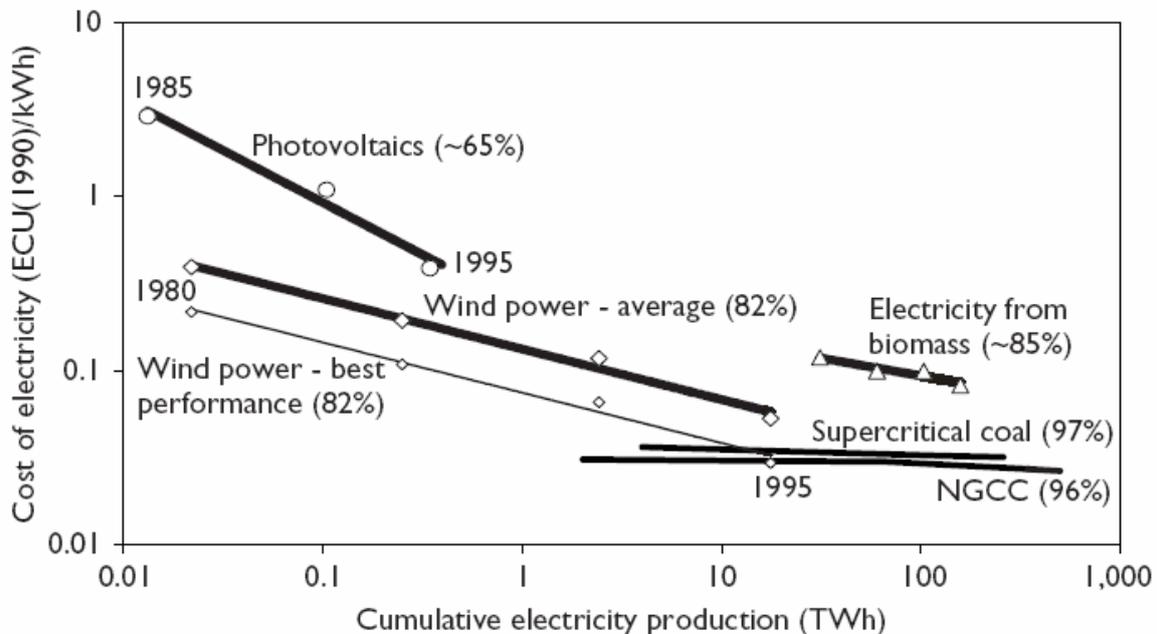
The concept of learning-by-doing is based on the observation that production costs or investment costs of a certain technology or product decrease with cumulated experience of producing it. Experience can be described in terms of cumulated production, output, sales or cumulative installed capacity. Often learning-by-doing is distinguished from learning-by-using or learning-by-researching. Whereas learning-by-doing refers to cost reductions that occur in connection with increasing experience in the production and installation of a specific technology, learning-by-using refers to cost reductions achieved by increased efficiency and experience in using a specific technology. Moreover, learning-by-researching refers to cost reductions that arise as a result of R&D activities (Löschel, 2002).

Hall and Howell (1985) distinguish learning curves from experience curves. According to their definition, the term learning curve indicates a relation between the costs of one of several, substitutable inputs (e.g. labor costs) and cumulative output (IEA, 2000), while the concept of experience curves is broader and refers to total costs, which allegedly occur over the total lifetime of a product (Boston Consulting Group, 1968). The experience curve,

relating total cost (C) of a technology and cumulative quantity (X), can be described by the following equation:

$$C = \alpha X^{-\beta} \quad (1)$$

where α reflects the base year cost, β is the learning elasticity (or learning index), which is used to calculate the relative cost reduction for each doubling of the cumulative production. With this definition, specific costs are reduced by a factor of $2^{-\beta}$ for every doubling of installed capacity. The amount $2^{-\beta}$ is defined as the progress ratio (PR) while $1-2^{-\beta}$ is called the learning rate (LR), e.g. a PR of 90% means that costs are reduced by 10% (LR) for each doubling of cumulative experience.



Source: IEA (2000). Cost of electricity and electricity produced from selected electric technologies installed in the European Union 1980-1995. Numbers in parentheses indicate estimates of progress ratios. The two curves for wind power show the average production costs and the production costs of the most efficient plant.

Figure 5.3 Learning effects for electricity technologies in the European Union, 1985-1990

Higher cost reductions and learning-by-doing can be observed for fast growing technologies that start out a low level of cumulative production, as a doubling of cumulative experience can be more easily achieved (McDonald and Schratzenholzer, 2001). Figure 5.3 illustrates learning in the European Union electricity sector between 1985 and 1990. Photovoltaic technologies show the highest learning rate, a cost reduction of 35% on average

could be achieved for each doubling of cumulative electricity output. This is followed by wind power, which yielded an 18% cost reduction for each doubling of output between 1980 and 1995. New large-scale fossil fuel technologies, such as supercritical coal technologies or natural gas combined cycle plants, show substantially lower cost reductions in relation to changes in output with learning rates at 3 to 4%.

A wide range of learning rate estimates for renewable energy can be found in the literature (Neij et al., 2004; Papineau, 2006; Junginger et al., 2005; Ibenholt, 2002; IEA, 2000). They differ because of varying assumptions with respect to time periods, cost measures (investment cost, levelized cost of electricity production, electricity or turbine price), experience measures (cumulated installed capacity, cumulative produced capacity, electricity generated), geographical area, system boundaries, data availability and quality, and estimation methods.³¹

5.3.1 Learning-by-doing in renewable energy machinery and equipment

Machinery and equipment components have substantially improved over time leading to lower unit costs. Such improvements for wind plants have been brought about by increased hub height, larger rotor blades, innovative technologies such as new direct-drive (gearless) systems, better foundations and site preparation, better equipment to respond more immediately to changes in direction and speed of wind, increased efficiency of generators, improved grid connection etc. (Neij et al., 2004). All these improvements are based on increased experience in the production of renewable energy machinery and equipment and contribute via learning to cost reductions. A typical learning curve would thus relate the unit cost of renewable energy equipment to the current or cumulated output of the industry. As plant size (capacity) differs among units, costs are usually expressed as specific plant costs per unit of generation capacity (€ per kW) and experience is measured in units of generation capacity (kW).

5.3.2 Learning-by-doing in renewable electricity production

In addition to learning in the production of renewable energy equipment, efficiency gains can be observed in the use of this equipment, i.e. in the production of renewable electricity. They include an improvement in identifying and making use of most favorable

locations, better information technology to respond to changing conditions, improved operation and maintenance, energy management, increased plant lifetime etc. Learning effects according to equation (1) can be estimated by relating levelized costs of renewable electricity production (€ per kWh) to cumulative experience measured in terms of electricity generated (kWh).

Most of these improvements reduce electricity costs but are not reflected in the capital cost. Some learning effects from the machinery and equipment sector, however, are carried over to the electricity sector in form of reduced investment costs. Thus, levelized costs of renewable electricity generation are lower not only because of learning in the production of electricity, but also because of learning in the production of machinery and equipment components. This implies that an approach, which estimates the cost reduction for renewable electricity production, covers the sum of both effects, and the learning effects for electricity production alone cannot be singled out.

Often, data on levelized costs of electricity production is not readily available and electricity price data is used instead. Using price data as a substitute means that mark-ups on costs (and more importantly changes thereof), as they may be caused for example by policy support or market power, have an impact on the estimation of learning. Learning estimates based on prices may thus under- or overestimate real learning. Up to now, learning has been estimated for the costs of renewable energy without distinguishing the source (industry) from which it originates. Also, the modeling of learning-by-doing attributed all learning to the electricity-generating sector. In the following sections, we explore the consequences of a more differentiated attribution of learning effects.

5.4 LEAN_2000

5.4.1 The model

In this study, the effects of learning-by-doing are examined using a modified version of LEAN_2000, a computable general equilibrium model. LEAN_2000 is a two-region empirical general equilibrium model for Germany and the rest of the European Union with a particular emphasis on the representation of the energy markets and the simulation of policies to reduce CO₂ emissions (Welsch and Hoster, 1995). Each region is represented in 15 sectors, seven of

³¹ Neij et al. (2004), for example, estimate experience curves for wind power in Denmark, Germany, Spain and

which are energy sectors (Table 5.1). LEAN_2000 is a recursive-dynamic model. Under the assumption of myopic expectations, it solves a sequence of static equilibria, which are connected via capital accumulation, technological change and exogenous assumptions on the development of some parameters. The model solves over a time horizon of 35 years from the base year 1995 to the year 2030. Crucial parameters, such as elasticities of substitution have been estimated (Welsch, 1996). The model is “calibrated”, that means the remaining parameter values are determined in such a way as to reproduce the data of the base period.

Table 5.1 Production sectors in LEAN_2000

| Production sectors | |
|---|---|
| Energy sectors 1. Hard coal and hard coal products 2. Lignite and lignite products 3. Mineral oil and mineral oil products 4. Natural gas and produced gases 5. Electricity 6. Nuclear fuels 7. Renewable energy | Non-energy sectors 8. Agriculture 9. Metals, minerals and chemicals 10. Equipment, investment goods 11. Consumption goods 12. Construction 13. Transport services 14. Other services 15. Non-market services (government) |

Production possibilities in each sector are represented by a nested constant-elasticity-of-substitution (CES) or fixed coefficient (Leontief) production function. Electricity production by different fuels is based on limited substitution possibilities because individual fuels are often used in different load sequences and thus cannot be easily substituted.

Private consumption is modeled by a representative household with a linear expenditure function. Consumption of each commodity consists of two components: a basic or subsistence consumption, which is consumed independent of income and prices and an additional consumption that depends on income and price level. **Public expenditure** is a linear function of GDP.

Aggregate **labor supply** is described by a dynamic wage equation, which explains wage formation by the dynamics of labor productivity in conjunction with a Philips curve

Sweden and reveal progress ratios in the range of 83% to 117% depending on the assumptions made.

mechanism. Labor is assumed to be mobile across the domestic sectors but immobile across borders. **Capital stocks** are fix within each time period and sector but change over time as capital depreciates and new investment is added. Sectoral investment is based on intertemporal cost minimization and depends on the interest rate, expected prices of variable input factors and expected demand.

Germany's most important **trading partners**, the European Union (EU) countries, are aggregated and explicitly modeled as one region. Trade flows between Germany and the rest of the EU are endogenous and depend on the relative prices of goods. **Foreign trade** with the rest of the world is modeled by means of a world trade pool with exogenous import volumes and export prices of the rest of the world. Foreign trade follows the Armington approach, modeling domestic and foreign goods as imperfect substitutes.

The model incorporates factor-augmenting **technical progress** for all production factors. For capital, technical progress is embodied. The average efficiency of each sector's aggregate capital stock can only be increased by introducing new, more modern equipment (Solow, 1962). For the other factors of production, technical progress is disembodied, meaning that it affects the total amount employed in each time period.

Because there is capital-augmenting technical progress, it is useful to introduce the concept of average capital efficiency. The efficiency of the existing sectoral capital stock (\tilde{K}_t) is a weighted average of the efficiency of last period's capital stock (\tilde{K}_{t-1}) and the efficiency of the latest vintage now in operation (\tilde{I}_{t-1}). In the original version, the efficiency of the latest vintage is assumed to grow at an exogenous rate.

$$\tilde{K}_t = \frac{(1-\delta)K_{t-1}}{K_t} \tilde{K}_{t-1} + \frac{I_{t-1}}{K_t} \tilde{I}_{t-1} \quad (2)$$

The following section describes how we modify this assumption to account for learning-by-doing.

5.4.2 Implementation of learning-by-doing in LEAN_2000

We introduce learning-by-doing on a sectoral basis in LEAN_2000. Learning is a function of the cumulative output in a sector. Due to learning, any given output can be produced at reduced costs because of increased efficiency in the use of factors of production.

Learning-by-doing can apply to the efficiency of both capital and labor input, i.e. factor-neutral, or can apply to only one production factor (factor-augmenting). In the case of capital input, learning-by-doing increases the efficiency of new investment, i.e. the latest vintage, \tilde{I} .

$$\tilde{I} = \left(\frac{X_{cum,t}}{X_{cum,0}} \right)^\beta \quad (3)$$

X_{cum} refers to sectoral cumulative output in period t and period 0 respectively, while β represents the learning index. As \tilde{I} enters the efficiency of the total capital stock, this implies that we endogenize capital embodied technological change. Similarly, we make labor efficiency a function of cumulated output and the learning index.

Implementing learning-by-doing into a dynamic-recursive model that solves for a sequence of temporary equilibria under myopic expectations means that future development, in particular effects from learning-by-doing, cannot be taken into consideration by decision makers in each period. This approach is well suited to represent market behavior as each individual actor has only a limited influence on learning and, therefore, does not consider it in its decision making process.³²

5.4.3 Renewable energy equipment in LEAN_2000

In our analysis, we assume that the production of wind turbines is part of the machinery and equipment sector. In order to account for material and equipment specifically used in the renewable energy equipment (such as the wind turbine) industry we introduce a new sector in LEAN_2000 called renewable energy equipment (EQIP), a sub-sector of the equipment sector. In 1995, the share of renewable based electricity was still at a rather small level (Figure 5.1). It is guesstimated that the value of output in renewable energy equipment accounted for only about 0.5% of the total value of output in the equipment sector in 1995 (VDMA, 2005a).

We assume that the inputs to the renewable energy equipment sector show the same pattern as the inputs to total equipment. On the use side (row IO table), we assume that products from the renewable energy equipment sector are used by one single sector, the electricity sector. In addition, renewable energy equipment is exported. We assume that

³² Learning may thus generate a positive external effect, which means market behavior may not lead to an optimal solution (market failure).

initially 0.5% of total equipment exports are to be allocated to renewable energy equipment exports.

5.5 Analysis and results

In order to explore the effects of learning-by-doing in renewable energy equipment and in renewable electricity production, we conduct three scenarios: (1) a **base case** scenario where no learning takes place in either sector; (2) a counterfactual scenario **lbd_elec** where learning-by-doing takes place in renewable electricity production; and (3) a counterfactual scenario **lbd equip** where learning-by-doing takes place in production of renewable energy equipment.

The base case scenario assumes a climate policy targeted at those sectors covered by the EU emissions trading scheme. In particular, we introduce a 20 Euros per t CO₂ in 2005, linearly increase it to 40 Euros per t CO₂ by 2010, and keep it constant thereafter. The climate policy equally applies to the two learning scenarios. For all three scenarios, assumptions about the development of the energy sector are in accordance with projections for Germany by IEA (1997) and Enquete (2002). Output of renewable energy in LEAN_2000 is exogenously given in accordance with the government goal for renewable electricity production. We assume wind power to be the single most important driver of growth in renewable energy with high initial growth rates that taper off over time. For renewable energy other than wind, we assume hydro capacity stable over time, as resources are limited, and allow for an increase in biomass- and waste-based electricity production. Additional baseline assumptions relate to prices of imported fuels, nuclear phase-out, and a minimum use of coal (FEES, 2007).

An exogenous path for renewable energy affects the way learning-by-doing can be analyzed. In this framework, learning-by-doing leads to a reduction of the unit costs of production, but not to an increase of the output of renewable electricity. For renewable energy equipment no output constraint is given. Since exports play a substantial role in this sector, production may increase even if domestic output of renewable electricity is exogenous. Learning induced cost reductions enhance (international) competitiveness and stimulate demand, which may then induce further learning.³³

³³ It needs to be stated that an exogenous path for renewable energy may be considered a constraint that impedes some of the effects on output that could result from learning induced cost reductions. We chose this approach as a simple approximation of the government development goals for renewable electricity production in Germany supported by the renewable energy law. We do not investigate which regulation or incentives are put in place to

A crucial parameter of the policy scenarios is the learning rate. Based on the literature review (section 3), we realize that learning rates for renewable electricity technologies have been in the range of up to 18% and more in the past, i.e. that the unit cost of renewable electricity production decreases by this rate for each doubling of cumulated output. In our analysis, we assume a more conservative learning rate of 10% for both learning scenarios. In the learning scenario `lbd_elec`, we assume that the cost reduction is due to an efficiency increase in the use of capital induced by learning in renewable electricity generation only. In the scenario `lbd equip` all cost reduction is attributed to learning-induced efficiency increases in the sector producing renewable energy equipment. Here we assume that the efficiency of the use of capital and labor is affected simultaneously. In the first scenario `lbd_elec`, learning reduces the costs of renewable electricity only, whereas in the second case `lbd equip`, it affects the costs of the relevant equipment as well and thus entails effects on international trade (compare Table 5.2). In another set of results shown in the Appendix, we conduct a sensitivity analysis and modify our assumption on the learning rate in the renewable energy equipment sector.

Table 5.2 Assumptions on learning rates in scenario analysis

| Scenario \ Sector | base case | scenario <code>lbd_elec</code> | scenario <code>lbd equip</code> |
|----------------------------------|-----------|--------------------------------|---------------------------------|
| renewable electricity production | - | 10% | - |
| renewable energy equipment | - | - | 10% |

5.5.1 Output, investment and price effects

This section presents the effects on output, investment and prices for the three scenarios (base, `lbd_elec`, `lbd equip`). We discuss the effects for each sector separately.

Effects on renewable energy equipment sector: In the base case, cumulated investment in renewable energy equipment as well as output of renewable energy equipment rise over time (see Figure 5.4 and Figure 5.5). This is to meet the capital demand of the renewable electricity sector with its exogenously given production goals.

induce the targeted increase of renewable energy, which implies that we do not model policy induced technology diffusion. In our approach, incentives for investment in renewable energy are based on export opportunities in addition to supplying the domestic market and crowding out imports.

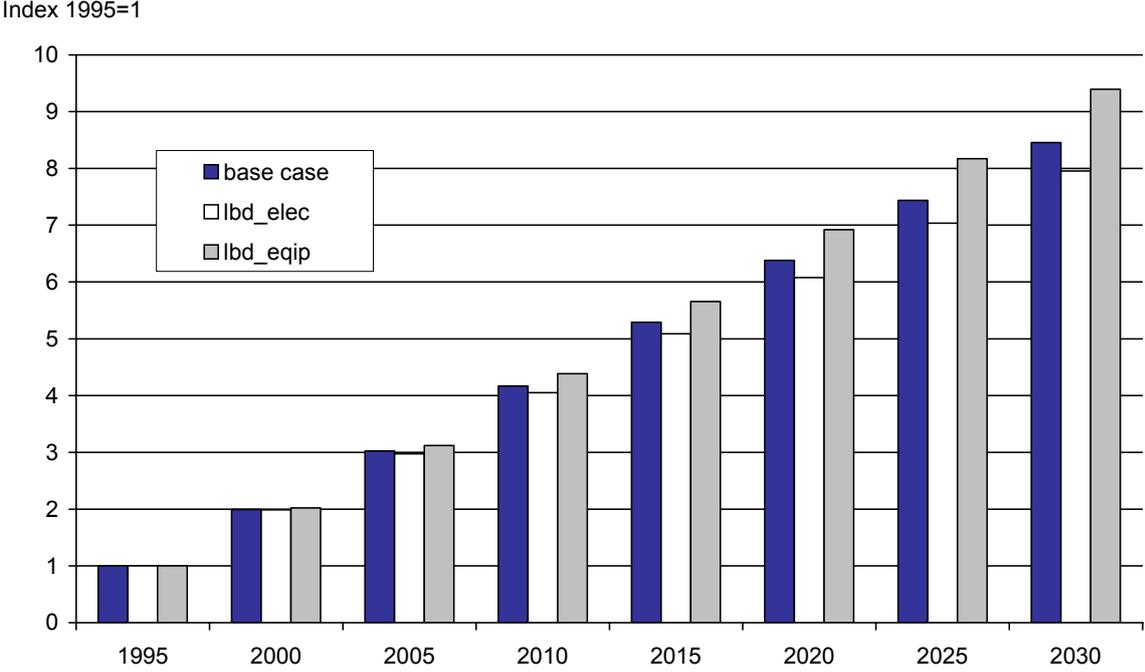


Figure 5.4 Cumulated output in the renewable energy equipment sector: base case and two counterfactual scenarios, indexed to 1995 thus reflecting quantity changes over time

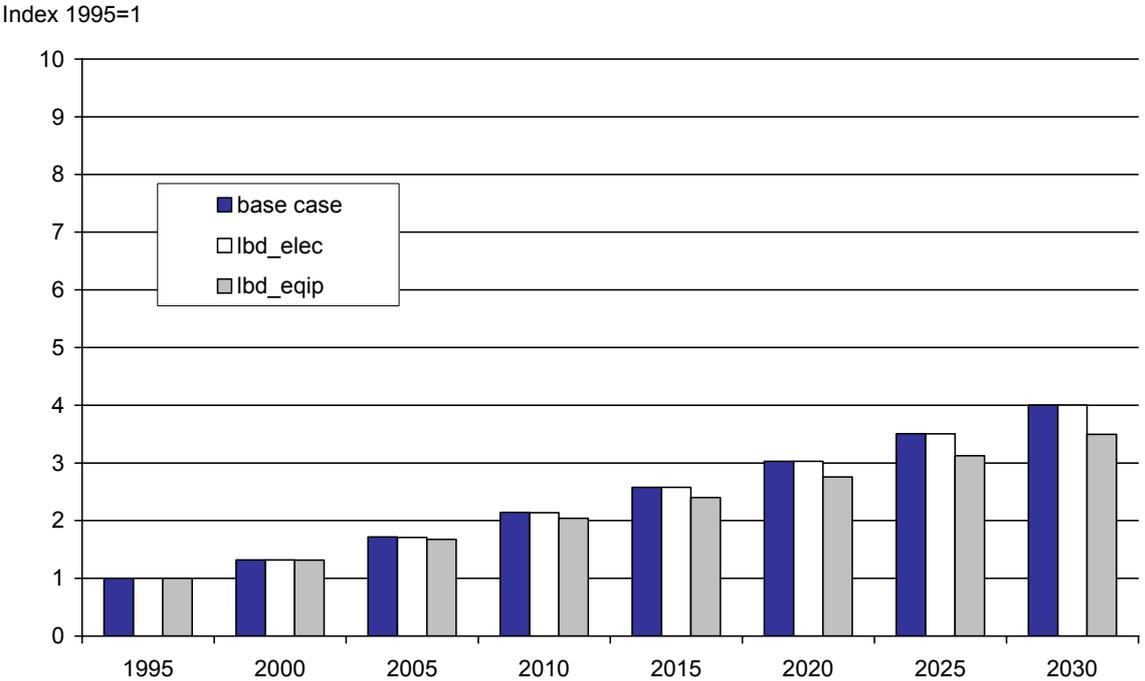


Figure 5.5 Cumulated investment in the renewable energy equipment sector: base case and two counterfactual scenarios, indexed to 1995 thus reflecting quantity changes over time

In the scenario where learning occurs in the production of renewable energy technologies (**lbd_eqip**), pronounced effects on production costs and output prices of the

sector can be observed (Figure 5.6). The decline in production costs increases export demand and thus spurs production, which then reinforces the learning effect. Therefore, cumulated output rises substantially (Figure 5.4) while cumulated investment in the renewable electricity sector in Germany (Figure 5.5) even declines slightly (compared to the base scenario) because capital efficiency increases while renewable electricity output is fixed.

With learning-by-doing in renewable electricity production (scenario **lbd_elec**) rather than in the production of equipment, capital productivity of electricity production increases and thus less investment is needed in renewable electricity production to produce a given electricity output. Consequently, demand for renewable energy equipment decreases slightly and cumulated output of the renewable energy equipment sectors is lower than in the base case. Accordingly, a small decrease in investment in the renewable energy equipment sector can be seen. The effect on prices is small.

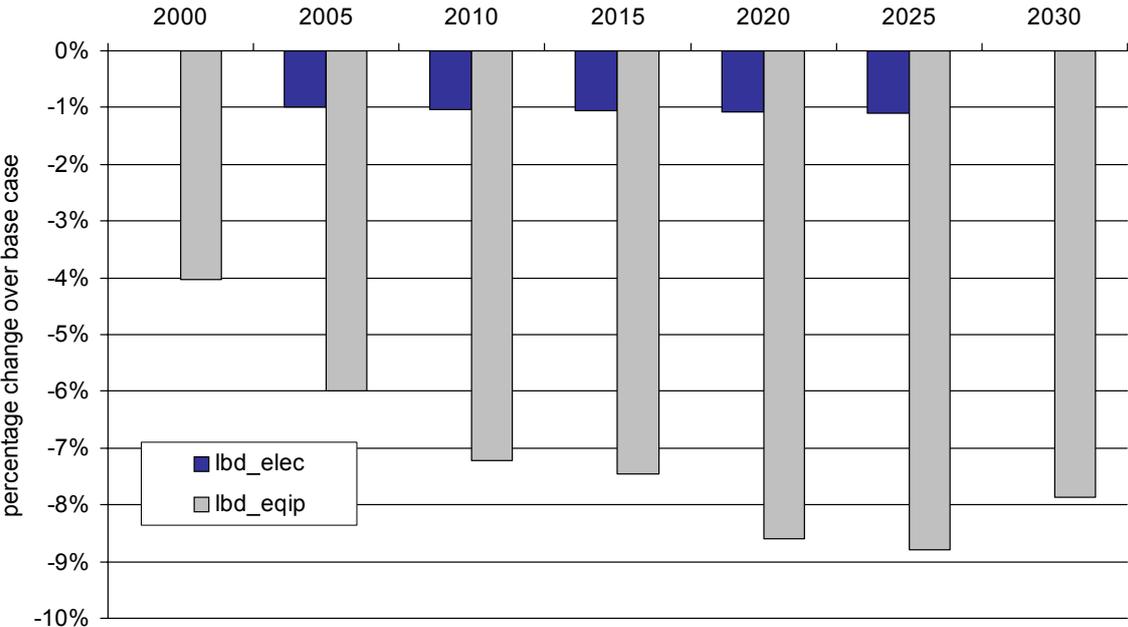


Figure 5.6 Output price renewable equipment sector, percentage change over base case

Effect on renewable electricity sector: In our model, output from renewable electricity production is exogenous and thus the same in all scenarios (as seen in Figure 5.7). Investment rises over time in the base case to meet the output goals of electricity produced by renewables.

With learning in the production of renewable energy equipment (scenario **lbd equip**), no change in cumulated electricity investment compared to the baseline can be seen. The same amount of capital as in the base case is needed to produce a given amount of electricity output

(Figure 5.7). However, learning induces a reduction in the costs of renewable energy equipment (Figure 5.6) and thus leads to increasingly lower unit capital costs for the renewable electricity sector. Equipment serves as one of two main inputs to electricity production. Therefore, the reduction of equipment prices translates into a decline of the price of renewable electricity output (Figure 5.8). The decline is not as pronounced as the reduction of equipment prices (Figure 5.6) because prices for inputs other than equipment are not affected.

With learning-by-doing in renewable electricity production (scenario **lbd_elec**), less investment is needed to produce a given amount of electricity output (as seen in Figure 5.7). Thus, cumulated investment in electricity production is lower than in the base case. The increase of capital efficiency leads to reduction of electricity prices (Figure 5.8). The price of renewable electricity declines over time compared to the base case as cumulated output increases and higher learning effects are induced. The decline in electricity prices is higher in the scenario where learning occurs in the electricity sector than in the scenario where learning occurs exclusively in the production of renewable energy equipment because the capital efficiency gain immediately translates into cost reductions.

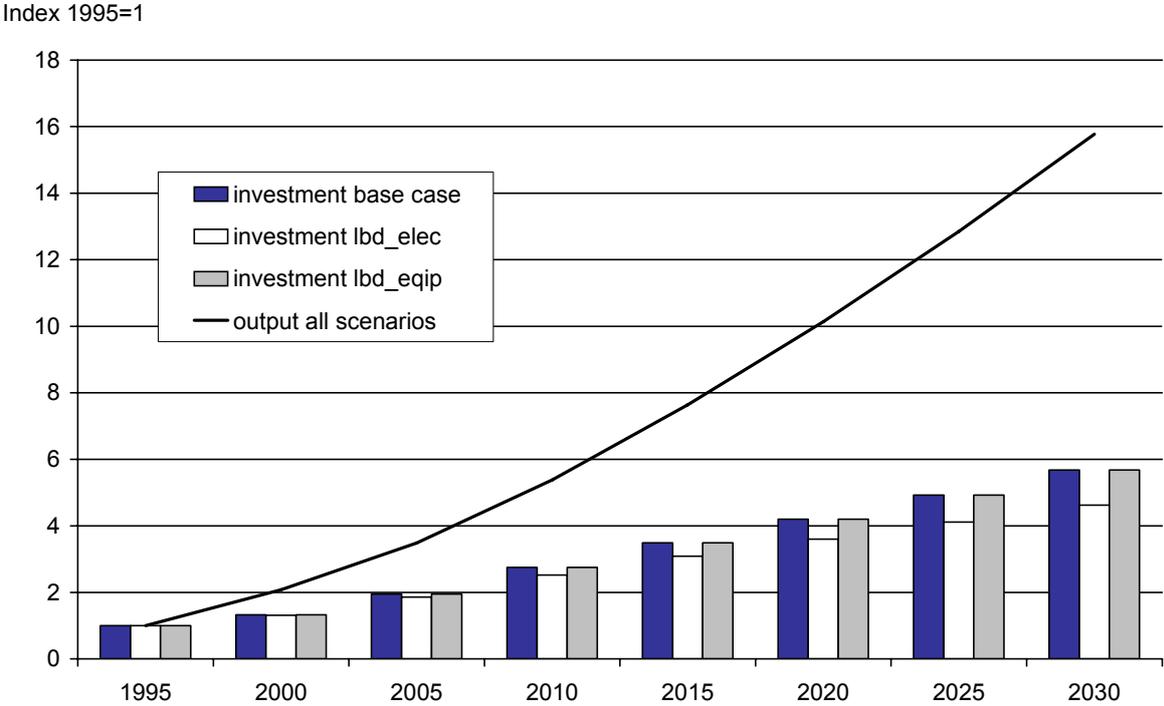


Figure 5.7 Cumulated output (line) and cumulated investment (bars) in the renewable electricity sector: base case and two counterfactual scenarios, indexed to 1995 thus reflecting quantity changes over time

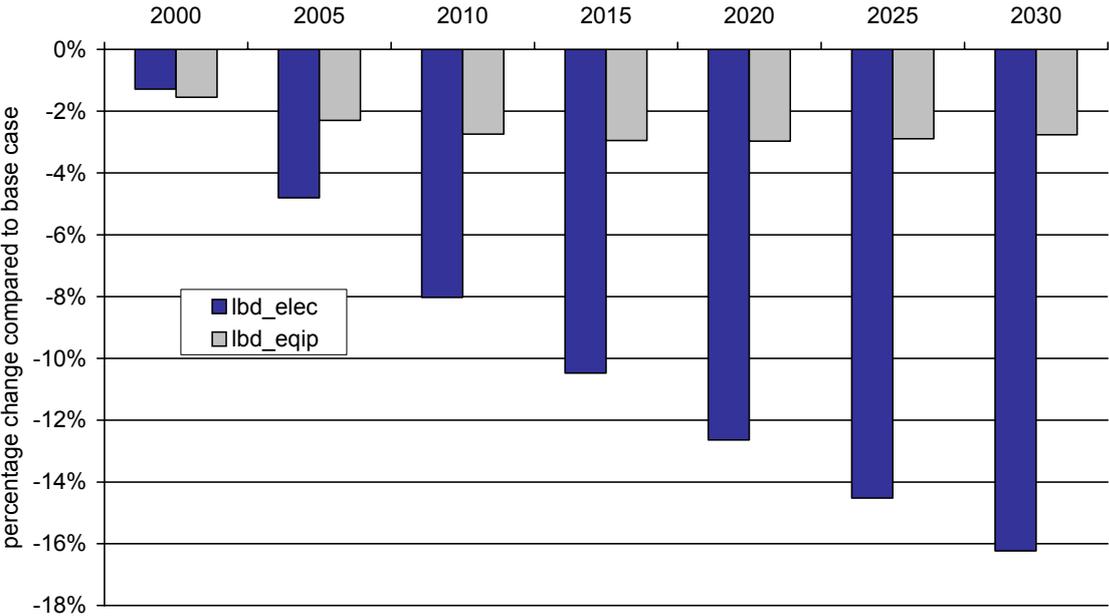


Figure 5.8 Output price renewable electricity, change over base case

To summarize, both counterfactual scenarios reveal effects on the price of renewable electricity. In scenario lbd equip the reduction in the price of renewable electricity production takes place through a reduction in the unit **cost** of capital investment (with capital efficiency in renewable electricity production constant) while in scenario lbd_elec the effect happens because of a reduced need for capital **input** per unit of output (with the costs of capital investment hardly affected). A learning rate of 10% in electricity production has a more direct and thus stronger effect than a 10% learning rate in the production of renewable energy equipment. To yield comparable effects on the price of electricity, we conduct another scenario where we choose a higher learning rate for renewable energy equipment in a way to produce comparable effects on electricity prices. The results are shown in the Appendix.

5.5.2 Macro-economic and international trade effects

As indicated above, the implementation of learning-by-doing in the renewable equipment sector (scenario lbd equip) stimulates an important effect on international trade. Exports in the sector are non-negligible (DEWI, 2006) and may even be more important in the future: On the one hand, (on-shore) locations are getting scarce and the expansion of wind energy generation may slow down in Germany, on the other hand, world markets for wind are likely to be growing. Exports of renewable energy technologies increase total demand for

renewable energy equipment and result in higher learning effects with its subsequent effects on costs and prices. This increases the international competitiveness of renewable energy equipment and may set off a virtuous circle: it stimulates international demand for this technology, which then again would induce higher learning (first-mover advantage). An analysis, which attributes all learning to the production of renewable energy electricity alone, does not take account of these international trade effects.

Figure 5.9 shows the development of domestic production and exports of renewable energy equipment compared to the baseline for the two learning scenarios. The positive effect of learning-by-doing in the industry producing renewable energy equipment can clearly be seen. Over time domestic production and exports increase significantly compared to the base case. Exports from Germany level off over time. However, the rise in domestic production continues as imports of renewable machinery to Germany are substituted by domestic production, which continues to become more competitive.

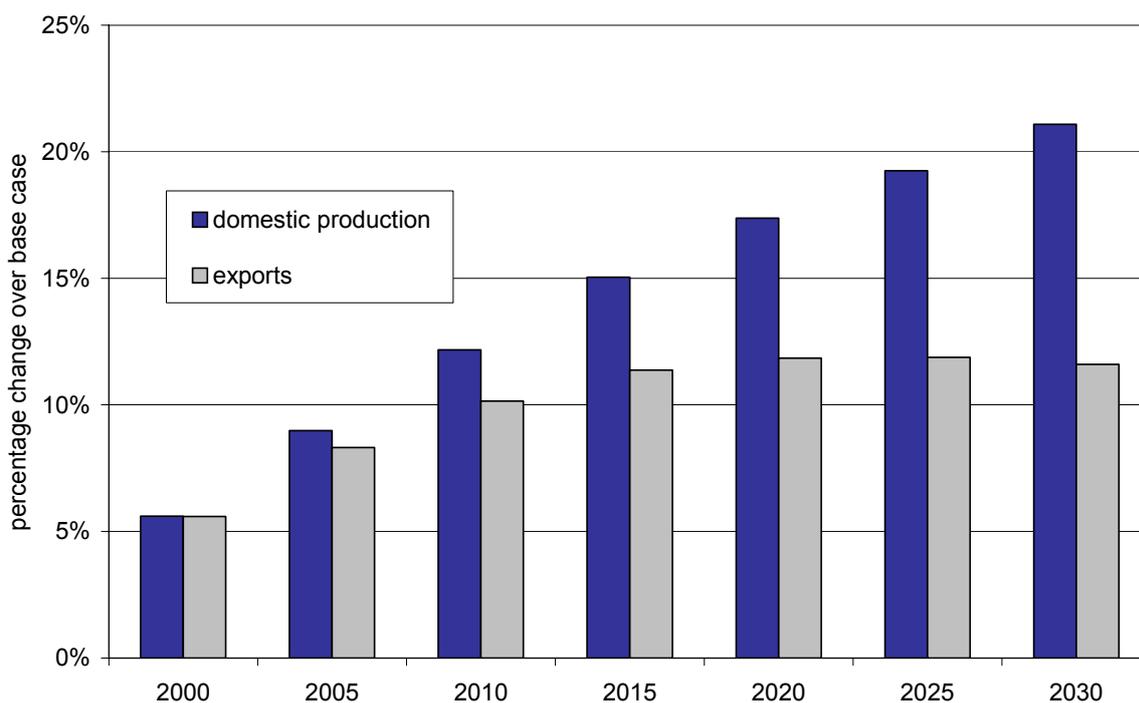


Figure 5.9 Domestic production and exports of renewable energy equipment: scenario learning-by-doing in renewable equipment, lbd_eqip (percentage change over base case)

The effects on GDP in Germany are shown in Figure 5.10. They are positive but small given the small share of the renewable equipment sector. Both learning scenarios lead to

positive effects because more capital resources are available for productive use in other sectors.

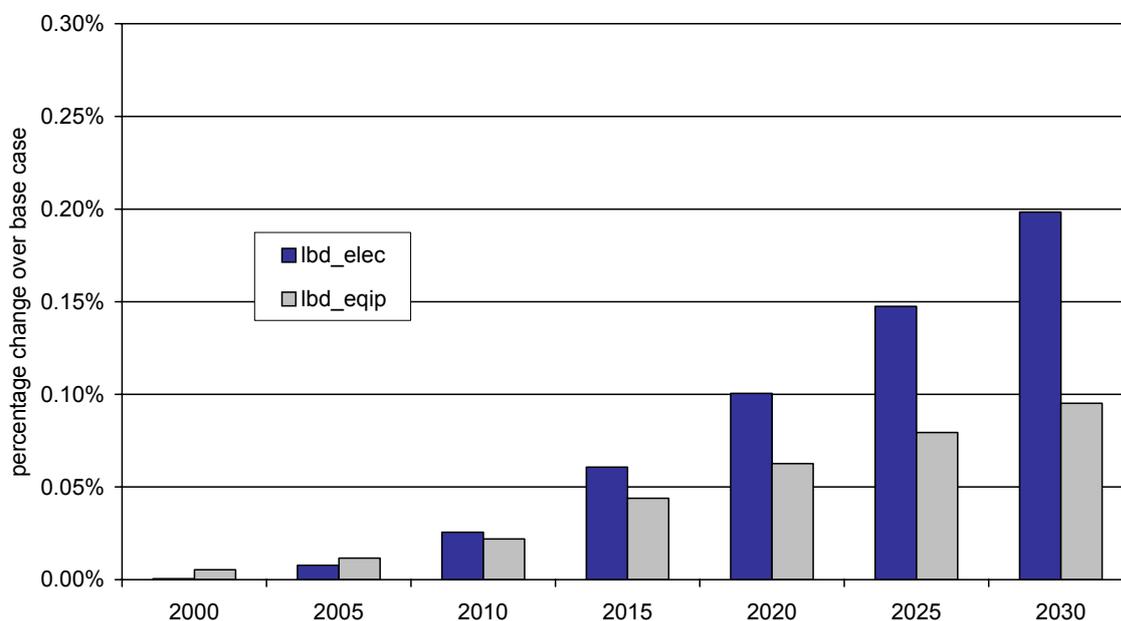


Figure 5.10 GDP real (percentage change compared to base case)

5.5.3 Energy and environmental effects

With respect to energy use, electricity production and the resulting CO₂ emissions we observe several effects. First, total electricity production in the base case as well as in the two scenarios declines over time. This is due to exogenous energy efficiency improvement (AEEI), to structural change in the economy as well as an increasing CO₂ price resulting from the EU emissions trading scheme. The drop in electricity production is highest in the base case. It is lower in the two learning scenarios because learning leads to higher GDP growth and a reduction in electricity prices, which stimulate demand for electricity. Second, the share of fuels used to produce electricity does not differ much among the three cases. With nuclear power being phased out over time and the quantities of renewable electricity fixed, fossil fuel use rises slightly. About two thirds of total electricity are produced by fossil fuels in 2000, by 2030 the share of fossil based electricity production increases slightly. For this reason, CO₂ emissions, which drop significantly at the outset, increase again until 2030 (Figure 5.12). The highest share of CO₂ emissions, however, comes from mineral oil use, which does not play a significant role in electricity production but in other sectors, such as transportation, chemicals industry or space heating. Since fuel consumption in private households and transportation is

not subject to the European Emissions Trading Scheme, we do not observe a significant change in fuel use in these sectors in response to a CO₂ price.

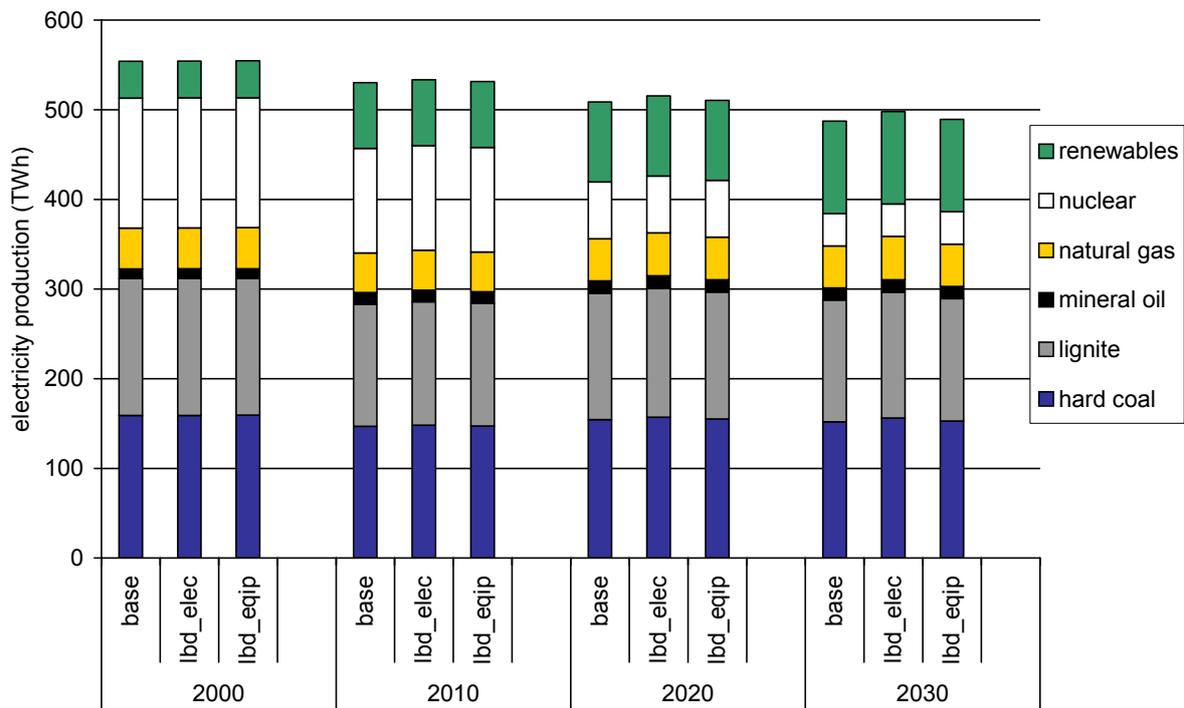


Figure 5.11 Electricity production (TWh) in Germany, 2000 to 2030

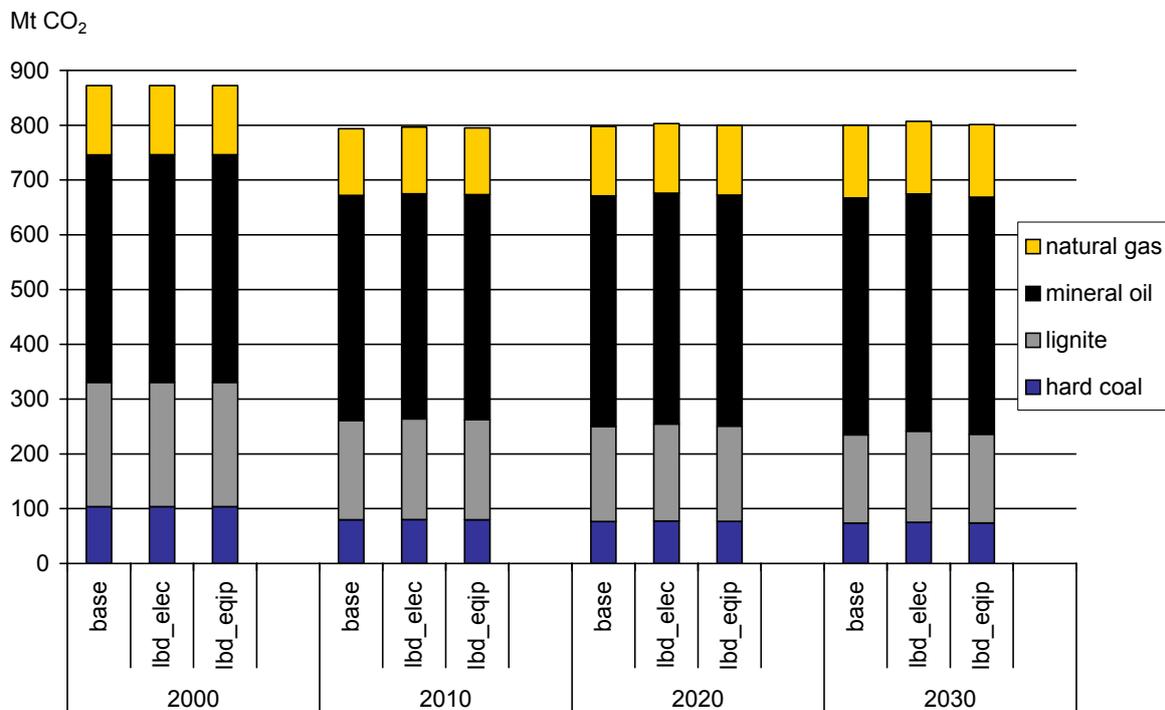


Figure 5.12 CO₂ emissions (Mt CO₂) in Germany, 2000 to 2030

5.5.4 Relative speed of learning and spillovers

The previous analysis assumes that learning by doing depends on economic activity in Germany only, i.e. that there are no international spillover effects.³⁴ Moreover, we assume that learning by doing takes place in Germany only. In this section we explore the effect of these assumptions on our results.

In the literature, alternative views of learning and spillovers can be found. Learning systems can be considered regional or global. While in a regional learning system, as simulated above, learning is restricted to the production of a certain country or region, global learning depends on and affects production in several countries. Learning should be considered global if, for example, producers of wind turbines learn from producers or employees from other countries and knowledge and technical know-how is transferred from one country to another. Such knowledge spillovers and the induced innovation and diffusion of new technologies have been intensively discussed in the climate policy literature.³⁵

In this section, we conduct a sensitivity analysis with respect to spillover effects. Our analysis so far is based on the assumption that there is no international knowledge spillover. We assume that Germany profits from learning-by-doing within its own borders based on domestic production of renewable energy technologies. Countries other than Germany experience no learning by doing or spillover effects. In light of the fact that Germany is now a major exporter of renewable energy technologies and its embodied know-how, but also that countries, such as Denmark in the case of wind turbines, provided much of the technology and know-how in the early stage of renewable energy development, several other cases can be distinguished (see also Table 5.3):

- 1) **Spillover Case 1** assumes that Germany cannot exclusively appropriate the benefits from technological learning within its own borders, because knowledge spillover takes place from Germany to other countries, i.e. learning-by-doing takes place in Germany and in the rest of Europe based on cumulated experience (output) in Germany. This

³⁴ On the other hand, it is implicitly assumed that learning provides an external effect, which spills over among domestic producers of either renewable energy equipment or renewable electricity in form of efficiency improvements in response to increase in total cumulated output of either industry.

³⁵ See for example Sijm (2004) for a thorough assessment of this issue. The concept of spillover effects has its origin in the literature on R&D and technological change. It refers to spillovers in the form of positive externalities such as R&D, knowledge, technology, and innovation transfer but also to negative externalities such as the transfer of emissions (carbon leakage) and environmental effects to other regions or countries (Weyant and Olavson, 1999; Jaffe et al., 2003; Grubb et al., 2002a). Weyant and Olavson (1999) define technological

means that countries other than Germany benefit from increased production experience in Germany and can apply the same technologies in their production processes or copy German products. As a consequence domestic production in, and exports from, Germany decline (compared to the scenario lbd_equip) as other countries appropriate state of the art development. This scenario would be most appropriate if Germany is seen as a technology leader and EU wide technology development solely depend on activities in Germany.

- 2) **Spillover Case 2** assumes that learning within both Germany and the rest of the European Union draws on cumulated experience gained not only within Germany but also within the rest of the European Union, i.e. on cumulated overall output in the EU. This means both Germany and the rest of the EU learn at the same rate. The effect is similar to the previous case. Domestic production and exports from Germany decline compared to the case without spillover effects as other countries benefit likewise from learning effects in response to increased experience. In our base scenario, we assume that growth of cumulated output is slightly higher in the rest of the European Union compared to Germany, with other countries pursuing similar (EU) renewable energy policy targets and catching up with Germany. Therefore, the cumulated output growth for Europe as a whole is also slightly higher, as Europe improves its competitiveness vis-à-vis the rest of the world. This means that learning effects in Germany are a bit more pronounced than in the previous case. Nevertheless, the effects on the economy (output/exports) are substantially lower than in the case without knowledge spillover where learning takes place in Germany only.
- 3) **Spillover Case 3** assumes that learning in the rest of the European Union depends on cumulated output within the rest of EU and learning in Germany depends solely on cumulated output in Germany. No knowledge spillover takes place but both regions experience learning effects within their own regions. In this case, learning is lower in Germany than in the rest of EU because cumulated output in Germany grows at a lower rate. Thus exports from and domestic production in Germany are smaller than in Spillover Case 2.

spillovers as ‘any positive externality that results from purposeful investment in technological innovation or development’.

Table 5.3 Assumptions for spillover analysis

| | Learning takes place in... | based on experience accumulated in |
|------------------|---|------------------------------------|
| No spillover | Germany | Germany |
| Spillover case 1 | Germany and rest of EU | Germany |
| Spillover case 2 | Germany and rest of EU | both regions |
| Spillover case 3 | Germany and EU for each region separately | |
| | i) Germany | i) Germany |
| | ii) rest of EU | ii) rest of EU |

Note: In all cases, learning refers to a cost reduction of 10% for each doubling of cumulative output in renewable energy equipment as outlined above.

The three cases are similar in that they allow knowledge to be accumulated in both regions, either as a spillover from Germany to the rest of the EU or in the last case as separate learning in each region.

We see that international knowledge spillovers dampen the benefit that Germany can draw from early investment in renewable energy technology. Figure 5.13 shows the results on domestic production and exports exemplified for spillover case 2 where learning takes place in each region based on total cumulated production of renewable energy technologies for all regions. Compared to the base case without any induced learning, all learning cases show a positive effect of learning-by-doing on export performance and domestic production in Germany, the effect, however, is more pronounced when there is no knowledge spillover between regions.

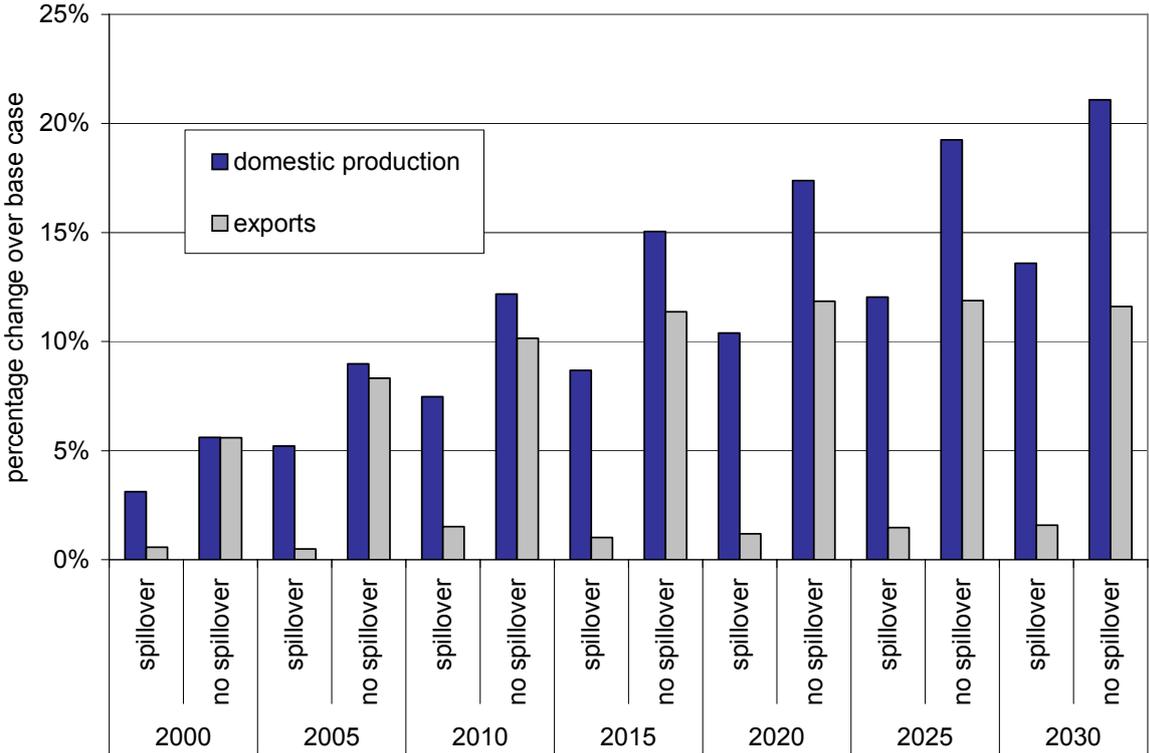


Figure 5.13 Domestic production and exports of Germany’s renewable energy equipment industry with and without knowledge spillover of learning in renewable energy equipment. In the spillover case, both Germany and the rest of the European Union experience learning in response to increased cumulated total output of both regions (Spillover case 2). In the 'no spillover' case, only Germany experiences learning in response to increased cumulative output within its own borders.

5.6 Summary and conclusions

Technological progress reduces the costs of renewable energies. When technological progress is induced via learning-by-doing rather than by autonomous efficiency improvement, this may have an influence on the optimal timing of environmental policies and of investment.

In previous analyses, all learning is commonly attributed to the renewable electricity sector, whereas it is quite evident that part of the learning takes place in upstream sectors, in particular in the production of renewable energy equipment. Our analysis shows that it does matter to differentiate between learning-by-doing in the renewable energy equipment and in renewable electricity production.

Two main effects take place by introducing learning-by-doing in the renewable energy equipment industry. Firstly, learning-by-doing leads to a reduction of the unit costs of equipment, which will, via capital goods (investment), translate into reduced renewable

electricity costs and prices. The second effect relates to international trade. Learning improves the international competitiveness of renewable energy equipment (first-mover advantage) and stimulates national and international demand for this technology, which then again may induce higher learning. Those effects and their stimulation of higher production activity and learning get commonly overseen when implementing endogenous technological change in the form of learning-by-doing in top-down energy-environment models. If learning-by-doing affects export sectors and improves international competitiveness this has consequences for the economic assessment of the costs and benefits of climate policy. Further analyses in this area may profit from the literature on international trade and its dynamics in the context of learning-by-doing (see for example Young, 1991).

The current empirical literature on learning by doing does not give any definite information in which sectors learning occurs or on spillover effects (Neij et al., 2004). The stylized modeling in this study may guide future empirical work distinguishing between sectors and incorporating spillover effects.

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5.8 Appendix

In this Appendix, we lay out some results from a sensitivity run to understand the significance of learning-by-doing in the renewable energy equipment sector. We modify our assumption on the learning rate in the renewable energy equipment sector and increase it to 40%, while we still assume a learning rate of 10% for learning that takes place in the renewable electricity sector.

This stylized scenario is constructed to highlight the effects of the two different modeling approaches. The learning rate for the renewable energy equipment sector is now chosen in a way to reveal similar effects on the price of renewable electricity. Both approaches now produce cost reductions for renewable electricity of a similar size (compare Figure 5.14). Learning in the renewable energy equipment sector is set to a higher rate because, in contrast to learning in the renewable electricity sector, it does not immediately affect the price of electricity. Learning-by-doing in the renewable energy equipment sector leads to a reduction of the unit costs of equipment needed to produce electricity. Together with unaltered costs of construction and labor input to electricity production, this equipment cost reduction translates, in a diluted way, into reduced renewable electricity costs and prices.

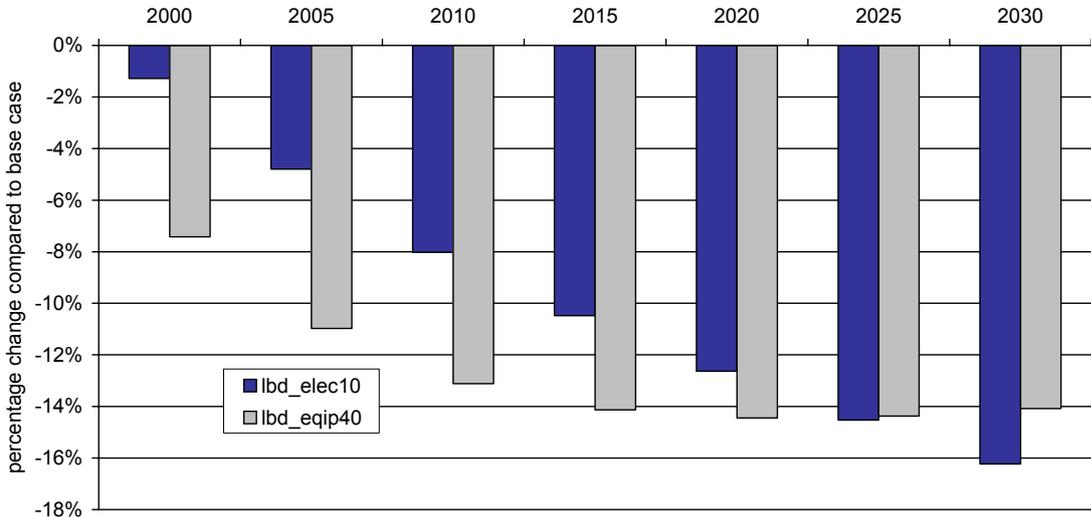


Figure 5.14 Output price renewable electricity with a learning rate of 10% for renewable electricity production and 40% for the production of renewable energy equipment, change over base case

In comparing the effects of a 10% versus a 40% learning rate in renewable energy equipment, we see that the fourfold increase in the learning rate yields a substantially higher

reduction of equipment prices (Figure 5.15). Although a 40% learning rate seems very high at first, it may not be unlikely for some renewable technologies, such as photovoltaic. The more pronounced decline in production costs at the higher learning rate triggers a likewise increase in export demand and a spur in domestic production as shown in Figure 5.16. This refers to the case with no knowledge spillover to other regions. Again as in the 10% learning scenarios, exports level off over time while domestic production continues to grow to meet demand and substitute for a decline in imports to Germany.

The effects on GDP are similar to the effects discussed in the main part of the study. They are positive and higher in the scenario with 40% learning in renewable energy equipment than in the 10% scenario. However, they are still relatively small (below 0.5%) given the small share of the renewable equipment sector in overall economic activity. This could change if total output of renewable energies were to increase more than in our simulations.³⁶

The analysis of spillover effects at a learning rate of 40% for the renewable energy equipment sector reveals similar trends as the 10% learning rate scenario, which is shown in the main part of the study. Figure 5.17 illustrates the extent of change. In the spillover case where learning takes place in each region based on total cumulated production of renewable energy technologies in all regions, domestic production and exports are lower than in the case with no knowledge spillover. The discrepancy between the two cases is more pronounced with higher learning. It shows that other regions can highlight benefit from mutual learning. Despite these spillover effects, Germany benefits from early investment in renewable energy technology and the more so the higher the learning rate.

³⁶ Renewable energy output was assumed to be exogenous in our simulations, reflecting policy targets of Germany and the EU. Higher output could be imposed exogenously or result endogenously from higher demand if renewables become more competitive.

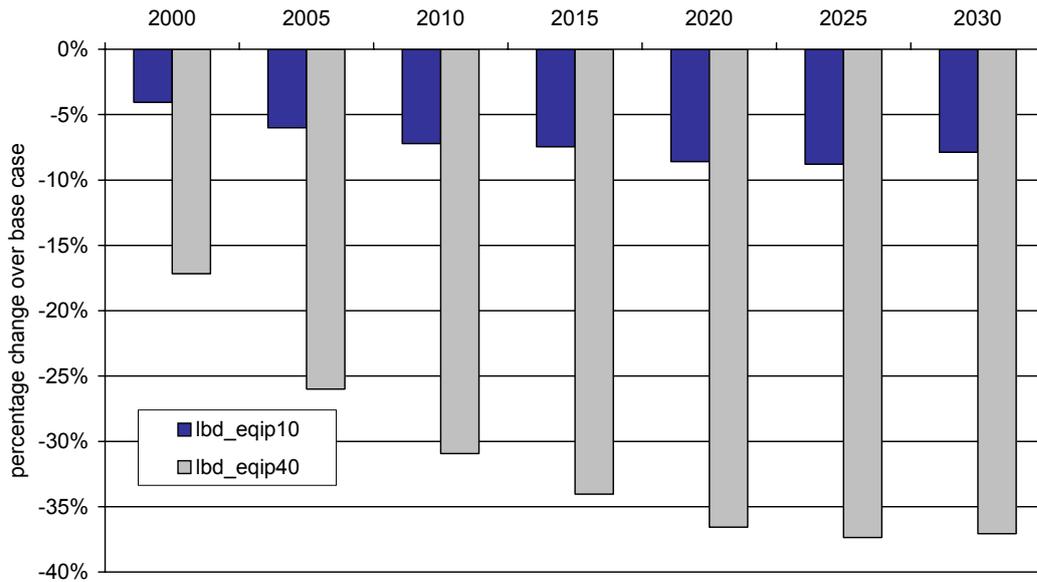


Figure 5.15 Output prices of renewable energy equipment at two different assumptions about learning rates in the production of renewable energy equipment: 10% (lbd_eqip10) and 40% (lbd_eqip40)

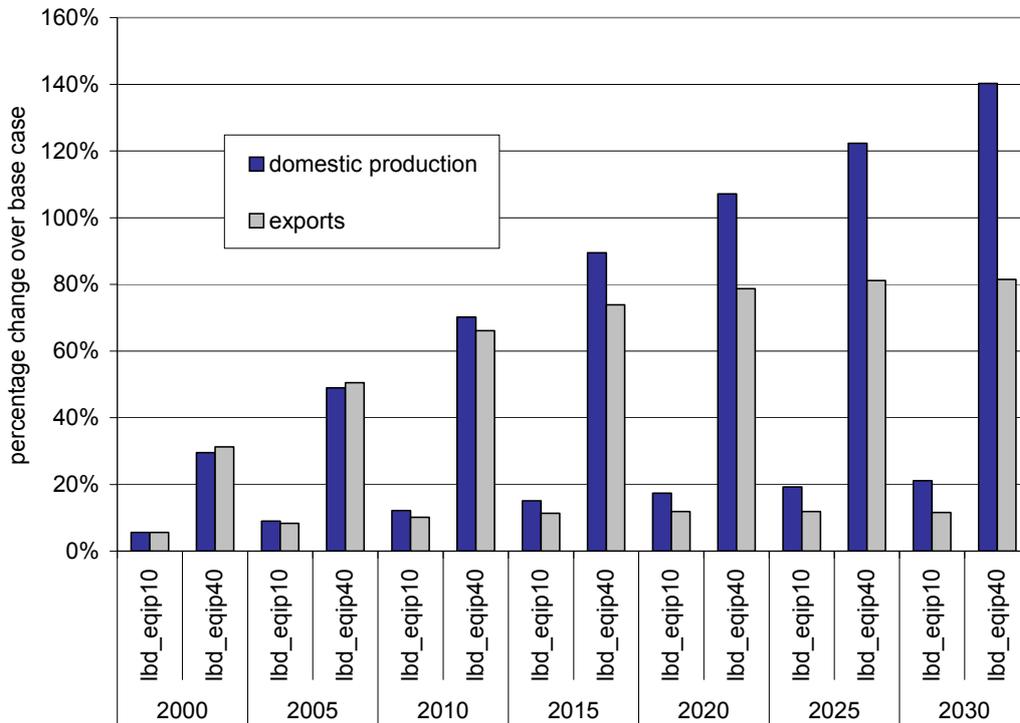


Figure 5.16 Domestic production and exports of the renewable energy equipment sector with a learning rate of 10% and of 40% for renewable energy equipment and no spillover effect

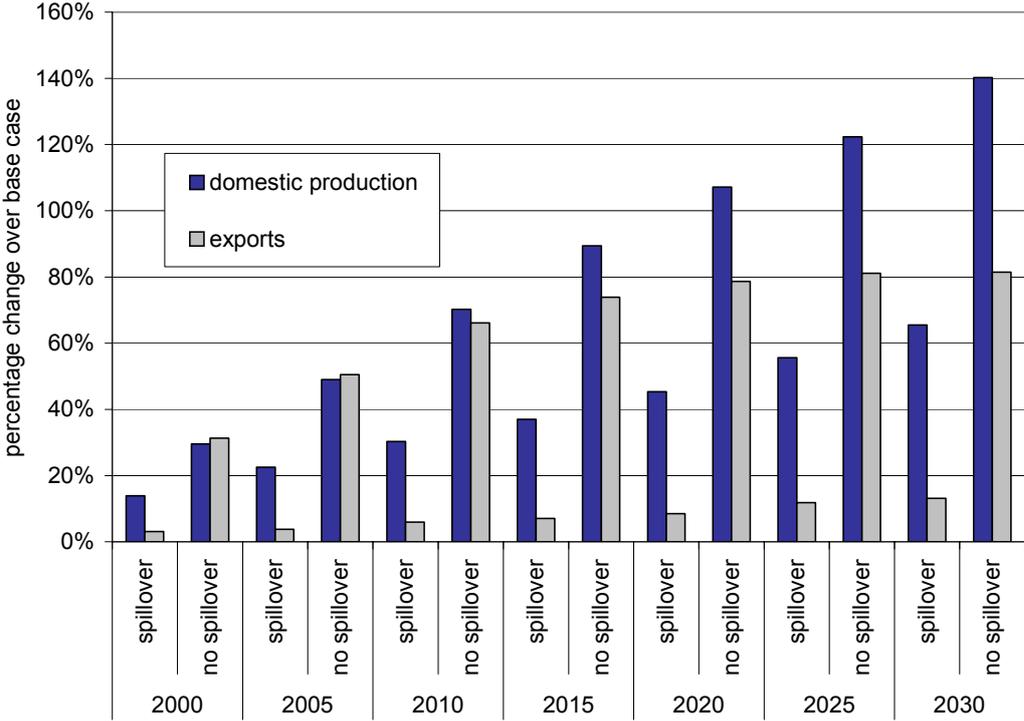


Figure 5.17 Domestic production and exports of the renewable energy equipment sector in Germany at a learning rate of 40% with and without knowledge spillover to and from the rest of the European Union

6 Summary and conclusions

For the analysis of energy and climate policies, top-down energy-economy models are used extensively. In these models, innovation and technological change are generally included either exogenously, through the introduction of specific technology description and assumptions on factor efficiency improvement, or endogenously as the result of investment in research and development or of learning-by-doing. This dissertation presents innovative ways of including innovation and technological change in energy-economy models. It explores methods for improving the realism of energy-transformation in top-down economic models. Hence, it develops novel approaches of treating technology innovations, and changes thereof, and provides different applications of these approaches to analyze the impacts of climate policy and innovation on economic activity, energy transformation and consumption, and associated environmental impacts.

This dissertation, thus, covers important methodological issues as well as policy relevant aspects of innovation and climate change mitigation. It reflects on the questions of (1) **how** to introduce innovation and technological change in top-down computable general equilibrium (CGE) models as well as (2) **what** additional and policy relevant information is gained from using these methodologies.

A top-down computable general equilibrium (CGE) modeling approach was chosen as the basis for analysis of energy and climate policy because it offers several advantages. CGE models have a good coverage of economic and environmental indicators (Böhringer and Löschel, 2006). They offer a consistent and systematic framework and perform well in the quantitative analysis of trade-offs between environmental quality, economic performance, and income distribution. Moreover, they provide a framework open to linkages with models or modules from other disciplines (natural science/biophysical, climate research, socio-economic behavior, engineering technology descriptions). In their application to energy-economy-environment analysis they are prominent because of their detailed representation of energy flows. Emissions are associated with fossil fuel consumption in production, investment and final consumption (Böhringer and Löschel, 2006a). Thus, both energy flows and related emissions are directly linked to economic activity. CGE models emphasize the interaction between energy and non-energy markets and simulate the combined economy-wide responses to price changes induced by policies or shocks. They allow for output adjustments, structural shifts, and for input substitution, and they keep track of simultaneous changes in input

intensity and associated emissions in all economic sectors. This implies that double counting of emissions is avoided and reductions in greenhouse gas emissions can be related to individual sectors.

There are several aspects CGE models are often criticized for: their lack of empirical evidence, the calibration to a base year, their lack of detailed sectoral and technical disaggregation, their restricted view on innovation and evolution thereof, their poor coverage of environmental indicators other than energy-related emissions, and the difficulties to reflect disequilibria, such as unemployment or under-utilization of production capacities (Böhringer and Löschel, 2006a). Some of these shortcomings have been tackled in recent studies and are specifically addressed in this dissertation. For example, the CGE model LEAN_2000, employed in this thesis, allows for disequilibria in the labor market by replacing the competitive labor market with a wage curve mechanism that allows for involuntary unemployment. Furthermore, the approaches shown in this thesis allow for detailed sectoral disaggregation and inclusion of a number of specific technological descriptions both on the supply and on the demand side of energy transformation. Chapter 4 specifically addresses the shortcoming of environmental indicators in allowing for non-CO₂ greenhouse gas emissions to be included into the analysis of climate policy.

The issue of innovation and technological change is the focus of this dissertation. Two new approaches to incorporate innovation and technological change are presented. The first approach is a hybrid approach where detailed technology descriptions are included into a CGE model not only on the energy supply side (specifically, electricity generation) but also on the energy demand side (specifically, the iron and steel industry). The primary strength of this hybrid approach is that it maintains the richness of engineering characteristics of key technologies, yet allows for a full general equilibrium analysis of energy or climate policies. It works at an intermediate level of technology detail, between the traditional aggregate production functions of top-down models and the extensive technology detail used in bottom-up models. It therefore immediately addresses the gap of bottom-up and top-down models. The approach permits a choice between several production technologies in selected sectors and allows for shifts in technology characteristics over time towards best practice, innovative technologies.

The second approach provides more insights into the effects of technological change, in particular learning-by-doing, in industries that are not immediately affected by climate policy but are responsible for delivering capital goods used in the energy sector. It therefore goes

beyond the conventional way of introducing learning-by-doing in energy or electricity producing sectors by separating out the impact of learning-by-doing in economic activities that are located further up in the production chain (such as machinery and equipment that produce renewable energy technologies).

Chapters 2 and 3 are devoted to the implementation of the technology-based approach. The analyses pursue two primary objectives. The first is to construct an advanced methodology for the analysis of energy and climate policy that links economic activity with energy technologies. The second is to provide plausible scenarios of energy consumption and emissions mitigation in Germany for the next several decades. Chapter 2 presents an application to conventional and advanced electricity technologies with and without the option of CO₂ capture and storage, while chapter 3 presents a first time application of the technology-based approach to an energy-intensive industry, namely iron and steel production.

The studies provide insights on the response of production sectors to policy-induced price changes, including changes in technology choice, in output, in the fuel mix and greenhouse gas emissions. In the context of climate change mitigation, the analysis reveals that it is important to model detailed electricity technologies together with detailed energy use in industrial processes in a consistent framework because greenhouse gas emissions from a specific industrial technology depend on the mix of electricity generation processes, which itself may change with a climate policy. The studies also show that shifts in technology are not singular events but continue over time as new investment decisions are taken. Thus, policies induce long-term shifts in production capacities, technological change and greenhouse gas mitigation.

The technology-based approach is an important step forward in representing industrial technologies in CGE models. In principle, CGE models are well suited to handle disaggregation of technologies and products, given sufficient data. The studies clearly demonstrate that it is constructive and feasible to operate CGE models at an intermediate level of technology detail. However, further research would be beneficial to fully exploit its potential:

First, even though the approach is much more detailed than typically found in a CGE model, it is less detailed than in some bottom-up linear programming models. One must make judgments as to the amount of detail to maintain and where to draw a system boundary around the processes modeled. Currently, there is little experience and no systematic study to guide this choice. Second, it remains difficult to find empirical support for the behavioral

parameters that determine the rate of shift between technologies as their relative costs change. It is also difficult to parameterize future advanced technologies. Other CGE and linear programming modelers must also determine important behavioral and technical change parameters. This challenge is inherent to all technology modeling and remains a challenge in our technology-based approach. These parameters deserve further country-specific, empirical justification. Third, even though we have added technology detail to the CGE framework, we still must characterize each production route with a single equipment lifetime. This means we have little capability to represent retrofit options and possibilities for lifetime extension. Fourth, we cover only one of the energy-intensive industries (iron and steel) besides electricity production. An analysis of the effects of climate policy in Germany would deserve technological detail for additional sectors, at least the set of major energy-intensive industries.

The next chapter (chapter 4) addresses an issue that CGE analyses have often been criticized for: the lack of extended greenhouse gas mitigation options (Böhringer and Löschel, 2006a; Scricciu, 2007). Therefore, this chapter specifically allows for reductions in non-CO₂ greenhouse gas emissions in addition to energy-related mitigation options such as energy efficiency improvement, fuel switching or introduction of CO₂ capture and storage. The study is designed to provide a balanced economic comparison of these different classes of mitigation options under a climate policy. Climate policy is represented by varying levels of a price for greenhouse gas emissions, either applied economy-wide or targeted to energy-intensive sectors of the economy according to the EU emissions trading scheme.

The study considers non-CO₂ greenhouse gas mitigation options to be end-of-pipe options that can be deployed relatively quickly on both new and existing capital equipment. Therefore, some of the non-CO₂ greenhouse gas mitigation potential is included in the baseline emissions scenario and a relatively small but still significant amount of additional reductions of non-CO₂ greenhouse gas emissions is available for policy scenarios. In contrast, the rate by which other greenhouse gas mitigation options, such as efficiency improvement, fuel switching, and CO₂ capture and storage, can be set up is generally limited by the rate that existing capital stocks retire.

This study provides more realistic scenarios of greenhouse gas mitigation options in Germany. Since Germany-specific marginal abatement costs curves for non-CO₂ greenhouse gases were not available, cost curves for the European Union were used instead. Further empirical work would be helpful to improve the quantitative estimates for Germany.

Chapter 5 is devoted to the implementation of learning-by-doing in renewable energy in a multi-sector, multi-region CGE model. Commonly, in such models all learning in renewable energy is attributed to the renewable electricity sector. However, it is quite evident that part of the learning takes place in upstream sectors that deliver capital goods to the electricity sector, in particular in the production of renewable energy equipment. The main novelty of the chapter is to alternatively consider the impact of learning-by-doing in the renewable electricity sector and in economic activities that are located further up in the production chain. The analysis shows that it does matter to differentiate between learning-by-doing in the renewable energy equipment and in renewable electricity production. The difference originates from the effect of international trade, since energy equipment, i.e. machinery and equipment that is used to produce electricity, is intensively traded on international markets, unlike electricity.

The implementation of learning-by-doing in the renewable energy equipment industry reveals two main effects.

- Firstly, learning-by-doing leads to a reduction of the unit costs of equipment, which, via capital goods (investment), translates into reduced renewable electricity costs and prices.
- The second effect relates to international trade. Learning improves the international competitiveness of renewable energy equipment (first-mover advantage) and stimulates national and international demand for this technology, which then again may induce higher learning.

An analysis of learning-by-doing effects in downstream production (e.g. electricity) alone is not able to take account of these international trade effects. In addition to international trade of a specific good, such as renewable energy equipment, knowledge and technical know-how about this good, which is responsible for learning processes, can spill over from one country to another. Depending on how such spillover effects are treated, substantial effects on domestic production and exports patterns can be observed. Our analysis reveals positive effects of learning-by-doing on export opportunities and domestic production in Germany. A main conclusion of this chapter is that, if learning-by-doing affects export sectors and improves international competitiveness, this has consequences for the economic assessment of the costs and benefits of climate policy.

The approaches and applications shown in this dissertation support the initial statement and prevalent agreement that it does matter to add technology-information in top-down

economic models devoted to the analysis of energy and climate policies. The technology-based approach applied to the electricity and iron and steel sector in this dissertation shows that it is important to consider technology detail within a broader and consistent economic framework. It improves the realism of policy simulations in capturing simultaneous adjustments in economic activity in response to mitigation policies. Future research would involve expanding this type of analysis to other industries and adding a wide set of technological information for each industry. Drawing on bottom-up modelers' extensive technology knowledge and data would be most beneficial. Further model development could also include endogenous adjustment of technological characteristics, such as through learning-by-doing or research and development investment.

The analysis may also be extended to other countries. This would provide the possibility to compare results between countries and incorporate effects on international trade, as it is shown in this dissertation for the analysis of learning-by-doing and spillover effects in Germany, the EU and the rest of the world. The stylized modeling of learning-by-doing in this dissertation may guide future empirical work distinguishing between sectors and incorporating spillover effects. Another important application may relate to the effects of technology transfer to developing countries. Specifically in the area of learning-by-doing, the analysis would further benefit from more refined empirical information and uncertainty analysis on sectoral learning rates and spillover effects.

Eventually it would be desirable to combine the approaches presented, add innovation and endogenous technical change for other sectors and countries, and link the modeling approach with models (or modules) from other disciplines to arrive at an integrated assessment of climate change mitigation options, and the associated economic, environmental and international trade effects.

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8 Erklärung

Erklärung über verwendete Hilfsmittel

Hiermit erkläre ich, Katja Schumacher, dass ich außer von den in der Danksagung genannten Personen keine weitere Hilfe von anderen Personen bei der Abfassung der Dissertation erhalten habe. Darüber hinaus habe ich außer der angeführten Literatur und den in der Dissertation angegebenen Hilfsmitteln keine weiteren Hilfsmittel verwendet. Ich bezeuge durch meine Unterschrift, dass meine Angaben über die bei der Abfassung meiner Dissertation benutzten Hilfsmittel, über die mir zuteil gewordene Hilfe sowie über frühere Begutachtungen meiner Dissertation in jeder Hinsicht der Wahrheit entsprechen.

Katja Schumacher

Berlin, den 10. April 2007