

**Analysis of Carbon Mitigation Policies: Feed-in Tariffs,
Energy and Carbon Price Interactions, and Competitive
Distortions on Carbon Markets**

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To Brigitte, Gerd, Lena, and Jonathan.

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Preface

The present thesis is a collection of essays written at the University of Kiel during my period as a doctoral candidate at the Institute of Economics. Chapters 1, 3, and 4 are joint work with Till Requate. Chapter 1 has been submitted for publication to *Energy and Resource Economics*, where it is currently in the second revision process. Chapters 3 and 4 are based on a policy report entitled *Emission Permits and Competition* commissioned by the Directorate for Financial and Enterprise Affairs of the Organisation for Economic Cooperation and Development (OECD). Lastly, Chapter 2 is joint work with Leonardo Morales-Arias. On the following pages I will provide a general introduction motivating the thesis topic and highlighting the research questions and main results of each chapter. After the last chapter I will present some general conclusions and policy recommendations.

Introduction

It is widely acknowledged by now that anthropogenic greenhouse gas emissions will cause increasingly adverse impacts on the earth's climate, ranging from rising global mean air and sea temperatures to an increase in natural disasters such as floods or draughts. According to the various assessment reports published by the Intergovernmental Panel on Climate Change (IPCC) since 1990, these climatic impacts will entail a variety of negative socioeconomic effects such as declining productivity of ecosystems, loss of human settlement areas, and implications for health (cf. IPCC, 2007). In 1992, when the United Nations proclaimed the goal of stabilizing the greenhouse gas concentration in the atmosphere at a level that prevents dangerous anthropogenic disruptions of the earth's climate, combating global climate change moved to the center of international environmental policy debates. Since then, a wide array of policy instruments has been put into practice aiming at limiting the increase in greenhouse gas emissions, in particular the emissions of CO₂.

These policy instruments can be broadly summarized in two categories. The first set of instruments applies to emissions directly by either defining a total emission cap or charging a price for emissions. The second set of instruments takes a more indirect approach by aiming at increasing the share of renewable energies, improving energy efficiency, or both, to reduce the use of fossil fuels and thus emissions in energy production. While the instruments in the first category define the reduction of emissions as the major policy goal, the instruments in the second category usually also follow other goals such as guaranteeing the security of energy supply and promoting innovation in the renewable energy industry.

The instruments summarized in the first category are emission taxes and tradable emission allowances. In the case of emission taxes the regulator defines

a price to be paid for each unit of pollution. In the case of emission allowances the regulator sets an overall emission limit and creates a market where emission allowances, each valid for one unit of pollution, can be traded. The introduction of a price or a cap on emissions has important repercussions for energy-producing and energy-intensive industries, since it turns CO₂ emissions from a free into a costly production factor and thus affects the production decisions of the firms. Under this kind of regulation, emitters required to pay a tax on their emissions or to hold a corresponding number of allowances will take their emission and abatement decisions by comparing their marginal abatement cost with the tax rate or the allowance price, respectively. In the most simple case, i.e. when there are no market imperfections, emission taxes and tradable allowances are equivalent and lead to an economically efficient result, implying that the total social cost of the policy is minimized.

Popular instruments in the second category are feed-in tariffs and tradable green certificates for renewable energies. Feed-in tariffs are production subsidies paid for electricity generated from renewable energy sources such as wind and solar power. In most currently implemented feed-in tariff systems, the tariffs are differentiated according to the production costs of the alternative renewable technologies, where the most expensive technology receives the highest tariff. The rationale is that most renewable energy technologies cannot compete on equal terms with conventional fossil-fuel and nuclear energies and would therefore not be able to penetrate the market without additional funding. However, the fact that the most inefficient technologies obtain the highest subsidy often leads to excessive costs associated with this policy. A more cost-efficient alternative in promoting renewable energies is the implementation of a tradable green certificate system. Similar to tradable emission allowances, such a system is based on setting a total quota for renewable energy, for instance in electricity production. In addition to selling electricity at the wholesale price, producers of renewable energies can sell certificates on the green certificate market to recover the additional costs incurred by producing renewable energy. Since a unique market price for green certificates is established, inefficient technologies will not be successful in the market. Therefore, green certificates imply lower total social costs than technology-specific feed-in tariffs. They are, however, still inefficient in abating

CO₂ emissions compared to the instruments in the first category. Indeed, the difference in marginal abatement costs of using renewable technologies such as wind and solar power and marginal abatement costs of traditional measures typically induced by emission taxes and allowances such as fuel switching and efficiency improvements is huge. For Germany, Frondel *et al.* (2010) and IEA (2007) currently estimate marginal abatement costs in the order of 700 and 1000€/ton CO₂, respectively, for photovoltaic and 50€/ton CO₂ for wind power. By contrast, since the introduction of the European emissions trading scheme in 2005, the allowance price has never exceeded the value 30€/ton CO₂.

In most countries there is not only one single climate policy goal but rather a wide array of different subgoals, including targets for CO₂ emissions, the share of renewable energies, particular renewable-energy technologies, the energy efficiency in different industries and sectors, and the share of biofuels in transport. To accomplish these different objectives most climate policies consist of a policy mix containing a combination of the above-mentioned instruments. However, combining different policy instruments may lead to overlapping regulations that usually give rise to distortions harming both the effectiveness, i.e. the ability of an instrument to reach the desired policy objective, and the economic efficiency of the policy. For instance, feed-in tariffs and other instruments promoting the production of electricity from emission-free sources are not compatible with emissions trading. The reason is that, due to the cap on total emissions defined by the emissions trading system, additional measures to reduce CO₂ will only reduce the market price for emission allowances but not the amount of allowances and thus emissions in the system. Therefore, if the policy objective is the reduction of CO₂ emissions, the only effect of renewable energy policies will be to distort cost efficiency without creating any additional emission reductions. If, on the other hand, there are other policy objectives besides reducing CO₂ emissions, an emission tax is more compatible with renewable energy policies than emissions trading. Since the tax rate is fixed, emission reductions achieved through the production of renewable energies will not be offset by increasing emissions in other sectors.

In the present thesis, I study several of the above-mentioned policy instruments for carbon mitigation with a particular focus on subsidies for renewable

energies, emission taxes, and tradable emission allowances by means of theoretical, empirical, and policy-oriented approaches. In the first chapter, I contribute to the analysis on overlapping regulations in emission and renewable energy policies by studying the optimal design and the welfare implications of two policy combinations consisting of (i) an emission tax for conventional fossil-fuel utilities combined with a subsidy for the producers of renewable energy equipment and (ii) an emission tax combined with a feed-in tariff for electricity produced from renewable sources. For this purpose, I consider a model with two types of electricity producers, an oligopolistic sector of polluting fossil-fuel utilities and a competitive fringe of non-polluting generators of electricity from renewable energy sources (RES-E), and an oligopolistic upstream industry of RES-E equipment producers engaged in learning by doing.

To preview some of the results in the first chapter with policy relevance I show that a first-best optimal policy requires two instruments, a tax in the fossil-fuel sector and an output subsidy for RES-E equipment producers. In the case that first-best optimal taxes are not available to the regulator, I derive second-best optimal feed-in tariffs paid to the generators of renewable electricity. By means of simulations I find that even under optimistic assumptions concerning the learning and spill-over rates in the renewable energy industry the learning effects have a small impact on social welfare compared to the impact of market power and pollution in the fossil-fuel sector. In particular, I show that if the regulator implements an emission tax amounting to only half of the optimal value, the welfare loss of a second-best optimal feed-in tariff policy will be significantly lower compared to a pure feed-in tariff policy. If first-best optimal emission taxes are feasible, the welfare effects of an additional second-best optimal feed-in tariff for renewable energies will even be almost zero. Moreover, in contrast to most currently implemented feed-in tariff policies including decreasing feed-in rates over time, the numerical results potentially call for a *short-term decrease* in feed-in tariff levels but a *long-term increase* in those levels as electricity markets are progressively liberalized. I therefore suggest that increasing the price for CO₂ emission would be a superior strategy, since higher costs of CO₂ and an expected decline in the share of nuclear electricity would lead to increasing electricity prices

and renewable energies would become more competitive and gain higher market shares even without subsidies.

The second chapter is devoted to the analysis of the empirical interrelationships between European emission allowance prices and prices for electricity, hard coal, and natural gas with an application to portfolio allocation. The motivation for this analysis arises from the fact that the introduction of an emission cap has important repercussions for energy-producing and energy-intensive industries in Europe. The emission constraint imposed on the European firms does not only directly affect the production costs of the firms, but also has indirect effects due to both rising electricity prices and relative changes in the prices of fuels with different emission intensities, particularly coal and natural gas. Therefore, optimal decision making requires a deep understanding of the CO₂ price dynamics and its interaction with other relevant commodity prices through the energy market. In particular, I propose a Vector Error Correction model (VECM) taking into account the (potential) long-run equilibrium relationship between electricity, emission allowance, gas, and coal prices, their short-run interactions, and exogenous factors such as temperature and rainfall indices, seasonal effects, crude oil prices, and economic growth rates. By means of an orthogonalized Generalized Autoregressive Conditional Heteroscedasticity (GARCH) error specification I identify the contemporaneous relationship between CO₂ and energy returns without imposing a-priori restrictions on the contemporaneous parameters. This approach is very useful to analyze, for instance, the impact of unexpected shocks on the endogenous variables. In addition to the analysis of the dynamic interrelationships between the emission allowance and energy returns, I study the performance of the empirical model in a dynamic portfolio allocation setting.

To preview some of the results in the second chapter with policy relevance I find that in the long run CO₂, gas, and coal prices are positively related to the price for electricity. By contrast, in the short run EUA prices seem to mitigate the impact of increasing coal prices on the electricity price. This is an expected effect indicating that increasing costs for coal-based electricity production will reduce demand for emissions and allowance prices. In the case of increasing natural gas prices the dampening effect on electricity prices via the allowance

price is not evident, indicating the possibility of fuel-switching from less emission-intensive gas to more emission-intensive coal. This result is interesting for policy makers since in the alternative case of regulating CO₂ emissions through taxes, a dampening effect on the wholesale electricity price would not occur. The results of the portfolio allocation application show that an investor holding a portfolio of the four commodities and a risk-free asset can improve the performance of his portfolio by engaging in dynamic trading strategies compared to a static trading strategy. This result can be relevant for financial investors and potentially also for firms wishing to hedge against price risks in their energy and emission commodity portfolio.

In the Chapters 3 and 4, I discuss further policy-related issues of emissions trading. One important question arising in the context of emissions trading, which is less pressing in the case of emission taxes, concerns the potential for market manipulations by firms holding a dominant position in the emission market, the output market, or both. For instance, dominant firms in the emission market may try to manipulate allowance prices to their advantage either by holding down supply or suppressing demand for allowances. Alternatively, dominant firms may try to abuse the allowance market to put their competitors in the output market at disadvantage. Finally, emission markets are not immune against illegal agreements and the formation of seller or buyer cartels. In Chapter 3 I therefore analyze the different forms of market power and their potential abuse in emission allowance markets and review the available empirical evidence on market manipulations in different emissions trading systems worldwide.

To preview some of the results in the third chapter with policy relevance I argue that the risk of abusing market power in emission markets is lower when the markets are sufficiently large and encompass firms from different sectors, the trading procedure is transparent, and there is a unique allowance price. In principle, this result holds independently of whether emission allowances are allocated for free or auctioned off. However, auctions might be more susceptible to bid shading and collusion than free allocation since it is clear a priori which firms are large buyers of allowances. Therefore, it is crucial to apply auction procedures preventing such behavior. Finally, applying emissions trading to small-scale pollution problems with only a small number of participants should not be ruled out

per se. However, since the potential for market power is larger in small emission markets, these markets require a stricter surveillance by competition and anti-trust authorities.

Another important source of competitive distortions arising from emissions trading systems may be attributed to unequal emission regulations across industries, sectors, regions, or countries. In particular, firms that are subject to tighter emission caps and thus face higher allowance prices may be at a competitive disadvantage compared to firms that are subject to less strict regulations. Moreover, in the international climate policy context many countries are either reluctant to impose unilateral emission limits at all or apply special provisions to protect their national industries from losing competitiveness on the global output markets. The different stringency of environmental policies worldwide may also give rise to carbon leakage if energy-intensive production is shifted to countries with less strict emission targets or none at all. The fourth chapter therefore analyzes competitive distortions arising from uneven conditions (i) between firms, industries, and jurisdictions regulated under the same emissions trading scheme, (ii) between industries in one jurisdiction regulated under different policy instruments, and (iii) between countries with different environmental regulations.

To preview some of the results in the fourth chapter with policy relevance I argue that the problem of competitive distortions due to unequal conditions within the same emissions trading system can best be solved through an auctioning system for allowances. Concerning the issues of international competitiveness and carbon leakage, I suggest that the countermeasures currently proposed to mitigate the adverse impacts of unilateral climate policies are highly imperfect, since they are almost ineffective in avoiding the indirect impact of emission policies on global energy prices. The empirical evidence on competitiveness effects arising from emissions trading in the energy-intensive industries indicates that, although it is not a general problem, it indeed affects certain industries more than others. This result is contingent on free allocation of allowances and might change if a larger share of allowances is auctioned off. The estimated carbon leakage effects also show a great variation across sectors, where the leakage rates may range from almost zero to more than 100 percent. Since leakage rates are lower when the coalition of countries participating in emissions trading increases,

the problems related to both international competitiveness and carbon leakage may best be solved by more and better international policy coordination.

Chapter 1

Subsidies for renewable energies in the presence of learning effects and market power

1.1 Introduction

Alongside issues such as the security of energy supply, the debate on global climate change and how to mitigate its adverse environmental effects has brought about political rethinking concerning the current and future use of fossil fuels. As a result, the promotion of renewable energy sources has become an energy-policy priority for many OECD economies. For instance, the member states of the European Union have agreed on binding targets to raise the share of renewable energies to 20 percent of gross final energy consumption by 2020. In terms of renewable electricity (RES-E) generation, the EU plans to source 21 percent of electricity consumption from renewable energy in 2010. Several other OECD countries such as Australia, New Zealand, Japan, Israel, and Korea, as well as a number of U.S. states have also announced renewable-energy and renewable-electricity targets with varying degrees of ambition.

Among the different national policies in the European Union, feed-in-tariff schemes have been particularly effective in promoting the rapid expansion of RES-

E capacity and production.¹ The United States also provides production subsidies for RES-E.² A popular argument in favor of subsidy policies such as feed-in tariffs is the existence of learning effects in the renewable energy industry. A number of empirical studies indicate that there is considerable potential for cost reductions through learning by doing in the wind turbine industry, the photovoltaic module industry, and other RES-E technologies (Grübler *et al.*, 1999; Hansen *et al.*, 2003; Isoard & Soria, 2001; Junginger *et al.*, 2005; McDonald & Schratzenholzer, 2001; Neij, 1997, 1999; van der Zwaan & Rabl, 2004). If this is the case, the allocation of subsidies is justified in the early stages of renewable resource use, as such subsidies encourage learning by doing and enable renewable energy producers to realize cost savings by moving downward on their learning curves. Without subsidies, these technologies would not be able to compete with fossil-fuel utilities. It is further argued that once learning has occurred and firms have eventually achieved competitiveness, the subsidies should be cut back.

From an economic viewpoint, however, public policy intervention is justified only if learning by doing generates spill-over effects benefiting other market participants without compensation. The spill-overs thus represent positive externalities that, together with the negative externalities through pollution, lead to an undersupply of new pollution-reducing technologies by the market (Helm & Schöttner, 2008; Jaffe *et al.*, 2005).

The model we develop in this chapter is based on three main strands in the literature. The first of these strands can be traced back to the seminal work by Buchanan (1976) and concerns the allocative inefficiency of Pigouvian emission taxes for imperfectly competitive firms. In the context of an imperfect market structure, there is a trade-off between the social gain from emission abatement and the social loss from monopolistic or oligopolistic output restriction, which

¹The highest feed-in-tariff rates are currently paid in Germany, where producers of onshore wind power installations are granted €0.092 per kWh during the first five years of operation (or more, depending on the efficiency of the installation) and the base rate of €0.052 per kWh subsequently. In the case of photovoltaic power the tariff for modules installed in 2009 lies between €0.32 and €0.43 per kWh.

²At the federal level, the Renewable Energy Production Incentive offers \$0.015 per kWh of renewable energy generation, denoted in 1993 US-\$ and indexed for inflation. Moreover, around 40 incentive programs are currently established in individual states, utilities, and through non-profit cooperations (cf. Database of state incentives for renewables and efficiency, <http://www.dsireusa.org/index.cfm>).

the regulator has to take into account when setting the tax rate (Barnett, 1980; Lee, 1975).

Second, there is a growing literature studying environmental policies in the presence of imperfectly competitive eco-industries (Canton *et al.*, 2008; David & Sinclair-Desgagné, 2005, 2010; David *et al.*, 2011; Requate, 2005). The term 'eco-industries' is used to refer to providers of abatement goods and services, such as the producers of RES-E equipment discussed in the present chapter. Assuming the polluting sector to be perfectly competitive David & Sinclair-Desgagné (2010) find that a first-best policy consists of a combination of pollution taxes and abatement subsidies.

The third strand analyzes the impacts of learning by doing and learning spill-overs on output, prices, and industrial structure. This large body of literature considers both monopolistic and oligopolistic markets (Fudenberg & Tirole, 1983; Spence, 1981) and perfectly competitive industries (Ghemawat & Spence, 1985; Petrakis *et al.*, 1997). According to Spence (1981), the main determinants of costs and firm performance in the presence of learning by doing are the learning rate, the extent to which the firm's costs decline through learning, the degree of learning spill-overs, and demand elasticity. Fudenberg & Tirole (1983) focus on the strategic interaction of firms in the presence of learning by doing when firms correctly anticipate the effect of their learning on their rivals' actions. In the context of environmental-economic models, the effects of learning by doing on the timing and total quantity of pollution abatement and on optimal policy instruments such as emission taxes and/or abatement subsidies have been studied by Goulder & Mathai (2000) for a single abatement technology and by Bramoullé & Olson (2005) for heterogeneous abatement technologies. However, neither of these studies considers the possibility of learning spill-overs, which represent an additional market failure as they lead to a divergence of social and private returns on learning by doing. In a recent paper, Fischer & Newell (2008) assess different policies for reducing CO_2 emissions and promoting renewable energy in the presence of technological progress through learning, R&D, and knowledge spill-overs. They conclude that in a perfect-competition framework an optimal portfolio of policy options will include an emissions price and subsidies for technological R&D and learning.

In this chapter we shall not consider technological progress through R&D but instead focus on the effects of learning and learning spill-overs in an imperfect-competition framework. In particular, we take account of the vertical structure of the renewable energy industry by assuming an upstream sector of RES-E equipment producers and a downstream sector of RES-E producers that buy the equipment and sell electricity to the consumers. Firms in the upstream sector can lower their costs through learning by doing, i.e. private learning and/or learning spill-overs. Furthermore, the producers of renewable electricity compete with conventional, fossil-fuel electricity producers. In the framework of a two-period model we assess two policy options: (a) an optimal policy consisting of an emission tax combined with an output subsidy for RES-E equipment producers, and (b) a feed-in-tariff policy where a subsidy is paid to the producers of RES-E. We assume the fossil-fuel industry to form a Cournot oligopoly, with an exogenously given number of firms. This is a realistic representation of the European and other OECD countries' electricity markets, which are usually dominated by a small number of large utilities. For the upstream RES-E equipment industry we consider both the case of perfect and imperfect (quantity) competition in the upstream market.³ The findings of Petrakis *et al.* (1997) indicate that, in the case of purely private learning, subsidies for RES-E producers should only take account of environmental damage but are not necessary to spur learning. In our model market power in the fossil-fuel and RES-E equipment industries creates additional distortions that the regulator has to take into account when deciding on subsidies for RES-E.

In the optimal policy the tax in both periods corrects for the marginal damage caused by pollution and for oligopolistic competition. With perfect competition

³The prevailing market structure in the RES-E equipment market is not so obvious. For example, the six market leaders in the wind turbine industry Vestas (Denmark), GE Wind (United States), Gamesa (Spain), Enercon (Germany), Suzlon (India), and Siemens (Denmark) accounted for 85 percent of the world market in 2008, but smaller expanding players such as Sinovel (China), Acciona (Spain), Goldwind (China), and Nordex (Germany) are stepping up competition in the market for wind turbines (BTM Consult, 2009). However, many wind turbine manufacturers are still mainly active in their domestic market and a few neighboring markets in the same region (Lewis & Wiser, 2007). For instance, Enercon, Vestas, and Siemens supply over 50 percent of the German, Dutch, and UK markets, respectively, Suzlon almost 70 percent of the Indian market, and GE Wind over 40 percent of the U.S. market (BTM Consult, 2009).

in the RES-E equipment industry, the optimal subsidy in the first period only takes account of the learning spill-overs neglected by the firms. In the case of an oligopoly of RES-E equipment firms, an optimal subsidy should also target the strategic effects induced by imperfect competition. Assuming that first-best levels of policy instruments are ruled out for political reasons, we then study a situation where subsidies are paid to the generators of renewable electricity, mimicking the common feed-in-tariff policy approach. We show that the second-best feed-in tariffs take account of environmental damage, distortions through market power and learning spill-overs. However, they perform much worse than first-best policies. A sensitivity analysis shows that both the ability of firms to learn via increase in their level of output and the size of the learning spill-overs have little impact on the performance of second-best optimal feed-in tariffs. The main factor with an impact on efficiency is the elasticity of electricity demand: the less elastic the demand, the higher the welfare loss of a second-best optimal feed-in-tariff policy will be in comparison with the first-best alternative. We also show that liberalization of electricity markets makes for decreasing feed-in tariffs in the short run but will raise these tariffs in the long run (when demand is more elastic).

The remainder of the chapter is organized as follows. In the next section we will set up the model. Section 1.3 will analyze the maximization problem of the social planner. In Section 1.4 we will illustrate the optimal policy in a decentralized economy. Section 1.5 will analyze a feed-in-tariff policy and derive the second-best optimal levels of the feed-in tariffs. We will then use a numerical example to investigate the effects of market structure on the size of feed-in tariffs and analyze the welfare effects of different policy combinations. Section 1.6 will summarize the results and draw some policy conclusions.

1.2 The model

We study a stylized electricity market with an exogenously given number of m identical oligopolistic fossil-fuel utilities engaging in quantity (Cournot) competition and a competitive fringe of RES-E producers with a continuum of firms. For

simplicity we assume that the fossil-fuel utilities use a unique, mature technology generating emissions of a single homogeneous pollutant. Output by a typical conventional utility is denoted by k_i . Its cost function is given by $K(k_i)$ and it has positive and increasing marginal costs, i.e. $K'(k_i) > 0$ and $K''(k_i) > 0$. Total output from fossil-fuel utilities is then given by $Q^f = \sum_{i=1}^m k_i$. Due to symmetry of the firms, total output of fossil-fuel utilities will be equal to mk in a social optimum and in market equilibrium, and therefore $Q^f = mk$. For simplicity we assume that emissions are proportional to the use of fossil-fuel inputs. Through appropriate choice of the social damage function we can write the damage as a function of the fossil-fuel utilities' output, i.e. $D(Q^f)$, with positive and constant or increasing marginal damage, i.e. $D'(Q^f) > 0$ and $D''(Q^f) \geq 0$.

The generation of RES-E is emission-free and RES-E firms are heterogeneous. Their cost function is represented by $C(q, \tilde{x})$, where q denotes output and \tilde{x} is a location parameter. This parameter reflects the assumption that the production cost of the RES-E generators depends on the location of their installations, e.g. wind turbines or solar panels. For instance, electricity produced by wind turbines is more effective and thus less costly at coastal sites, where the wind blows more steadily than at sites further into the countryside. In the case of solar panels, electricity production is more effective at sites with stronger solar radiation than at more cloudy sites. Besides being more realistic than simply assuming the downstream firms to be symmetric, this assumption also induces a nicely downward-sloping inverse demand function for RES-E equipment. The cost function of the RES-E producers satisfies $C_q > 0$, $C_{\tilde{x}} > 0$, $C_{qq} > 0$, $C_{q\tilde{x}} > 0$ for $q < \bar{q}$, where \bar{q} is the maximal capacity, for instance, of a wind turbine. Marginal costs are positive and increasing in both output and the location parameter. The increasing marginal cost can be explained by maintenance costs. The better is the maintenance the higher is the efficiency and the lower is the probability of default. We further assume that $\lim_{q \rightarrow \bar{q}} C_q(q, x) = \infty$. In other words, perfect maintenance becomes prohibitively expensive. Moreover, to guarantee that second-order conditions are satisfied, we assume overall convexity of the cost function, implying $C_{\tilde{x}\tilde{x}} > 0$ and $C_{qq}C_{\tilde{x}\tilde{x}} - [C_{q\tilde{x}}]^2 > 0$.

Besides the producers of electricity, we consider an upstream sector of RES-E equipment producers with an exogenously given number of n symmetric firms,

characterized by their cost functions. Since we assume that RES-E equipment producers engage in learning by doing, we have to consider at least two periods $t = 1, 2$. Hence, we let $\Gamma^1(y_{1i})$ and $\Gamma^2(y_{2i}, L_i)$ denote upstream firm i 's cost in period 1 and 2, respectively, where y_{ti} is firm i 's output level in $t = 1, 2$. A firm's cost in $t = 1$ is solely determined by its own output, while in $t = 2$ costs also depend on a variable L_i representing the experience gathered by firm i . The experience in the second period depends on firm i 's own level of production in the first period y_{1i} (private learning) but also on the other firms' aggregate output in the past multiplied by the degree of learning spill-overs (ε). Thus experience is given by $L_i = y_{1i} + \sum_{j=1, j \neq i} \varepsilon y_{1j}$. For $\varepsilon = 0$ learning is purely private, while for $\varepsilon = 1$ there are complete learning spill-overs, implying that for a single firm it does not matter whether it produces one additional unit itself or whether the other firms do so.⁴ In a symmetric allocation the aggregate experience is the same for each firm, i.e.

$$L = [1 + (n - 1)\varepsilon]y_1. \tag{1.1}$$

The cost function of the RES-E equipment producers satisfies the following properties: $\Gamma_{y_t}^t > 0$, $\Gamma_{y_t y_t}^t > 0$, i.e. positive and increasing marginal costs in output, and $\Gamma_L^2 < 0$, $\Gamma_{Ly_2}^2 < 0$, i.e. lower costs and marginal costs in the second period due to learning by doing. Further we assume that $\Gamma_{LL}^2 > 0$, implying that the marginal effect of learning is decreasing. To guarantee satisfaction of second-order conditions we again assume overall convexity of Γ^2 through

Condition 1 : $\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - [\Gamma_{Ly_2}^2]^2 > 0$.

Condition 1 implies that the "own-convexity" effect dominates the cross-effect and also guarantees satisfaction of the second-order conditions for both the social optimum and the firms profit maximum under decentralized decision making.

For simplicity we assume that each downstream firm buys only one RES-E equipment unit, e.g. one wind turbine, per period. Since the downstream firms are asymmetric, we denote the output of firm \tilde{x} by $q_t(\tilde{x})$. Furthermore, we use X to represent the marginal location above which the downstream firms do not

⁴There is little empirical evidence on the size of spill-over effects in the renewable energy industry. One of the few studies in field is by Irwin & Klenow (1994) who estimate a spill-over coefficient of about $\varepsilon = 0.33$ in the semiconductor industry.

produce. Therefore, due to $C_{\tilde{x}} > 0$ and $C_{q\tilde{x}} > 0$, it is efficient that all firms with $\tilde{x} < X$ produce if the firm at location X produces. This argument is also consistent with the behavior of the downstream firms in a decentralized economy. If it is profitable for the marginal firm at location X to produce, the same must hold for any $\tilde{x} < X$. We can also interpret X as the total number of RES-E equipment producers in the market in each period t , so in a symmetric allocation

$$X_t = ny_t \tag{1.2}$$

represents the total output of RES-E equipment and hence the total capacity installed in t . Total output by fossil-fuel electricity generators in period t is given by $Q_t^f = mk_t$ and total "clean" electricity by $Q_t^c = \int_0^{X_t} q_t(\tilde{x})d\tilde{x}$ such that overall total output is

$$Q_t = Q_t^f + Q_t^c = mk_t + \int_0^{X_t} q_t(\tilde{x})d\tilde{x}. \tag{1.3}$$

We denote demand for electricity by a downward-sloping inverse demand function

$$p_t = P_t(Q_t) \tag{1.4}$$

satisfying $P_t''(Q_t)Q_t + P_t'(Q_t) < 0$, implying that the inverse demand function is not too convex. Anticipating a symmetric allocation, we are now ready to define welfare as

$$\begin{aligned} W = & \int_0^{Q_1} P_1(Q)dQ - mK_1(k_1) - \int_0^{X_1} C^1(q_1(\tilde{x}), \tilde{x})d\tilde{x} \\ & - n\Gamma^1(y_1) - D_1(mk_1) + \delta \left[\int_0^{Q_2} P_2(Q)dQ - mK_2(k_2) \right. \\ & \left. - \int_0^{X_2} C^2(q_2(\tilde{x}), \tilde{x})d\tilde{x} - n\Gamma^2(y_2, L) - D_2(mk_2) \right], \end{aligned} \tag{1.5}$$

where δ denotes the discount factor.

1.3 The social optimum

Before we study the optimal policy instruments, it is useful to characterize socially optimal allocations. The social planner maximizes welfare with respect to $q_t(\tilde{x})$, k_t , and y_t . The first-order conditions are given by the following equations:

$$W_{q_t} = P_t(Q_t) - C_q^t(q_t(\tilde{x}), \tilde{x}) = 0, \quad t = 1, 2, \quad \tilde{x} \in [0, X_t], \quad (1.6)$$

$$W_{k_t} = P_t(Q_t) - K'_t(k_t) - D'_t(mk_t) = 0, \quad t = 1, 2, \quad (1.7)$$

$$\begin{aligned} W_{y_1} &= P_1(Q_1)q_1(X_1) - C^1(q_1(X_1), X_1) - \Gamma_{y_1}^1(y_1) \\ &\quad - \delta[\Gamma_L^2(y_2, L)(1 + (n-1)\varepsilon)] = 0, \end{aligned} \quad (1.8)$$

$$W_{y_2} = P_2(Q_2)q_2(X_2) - C^2(q_2(X_2), X_2) - \Gamma_{y_2}^2(y_2, L) = 0. \quad (1.9)$$

The interpretation of the conditions for a welfare maximum is straightforward.⁵ (1.6) requires that the optimal price of electricity, corresponding to the consumers' marginal willingness to pay, must be equal to marginal costs in the RES-E generation sector in each period, while (1.7) implies that in every period the marginal willingness to pay must equal the sum of marginal costs and marginal damage for the fossil-fuel firms. As (1.6) holds for all $\tilde{x} < X_t$, it also determines the optimal number of RES-E equipment units in each period. Note that $P(Q)q(X) - C(q(X), X)$ represents society's marginal willingness to pay for RES-E equipment. Therefore, (1.8) and (1.9) imply that this marginal willingness to pay equals the marginal costs of RES-E equipment producers in each period. Equations (1.8) and (1.9) thus define the optimal individual output levels for the upstream producers. Since learning occurs in $t = 1$, the effects on marginal costs of both private learning and learning spill-overs are included only in equation (1.8). Due to $-\Gamma_L^2 > 0$, (1.8) implies that $\Gamma_{y_1}^1(y_1) > P_1(Q_1)q_1(X_1) - C^1(q_1(X_1), X_1)$. Thus it is optimal to set a production level of RES-E equipment with marginal cost of production exceeding the private benefit to consumers in $t = 1$, because more output in $t = 1$ decreases the costs of all other RES-E equipment producers in $t = 2$.

⁵Since the welfare function is the sum of concave functions it is also concave and therefore the second-order conditions are satisfied (Takayama, 1997).

1.4 Optimal policy

In this section we consider decentralized decision making and optimal regulation of markets. Since Cournot-oligopoly is the prevailing market structure on the electricity markets in most countries, we assume that the fossil-fuel producers act strategically when choosing their level of output, while the RES-E operators act as a competitive fringe. Both kinds of electricity producers, however, make their output decisions simultaneously. Concerning the RES-E equipment producers the existing market structure is not so obvious. As BTM Consult (2009) reports for wind energy, in some countries such as France, Germany, Italy, and China there is quite a large number of wind turbine suppliers, while in other countries such as India, the Netherlands, and the UK the market is governed by only two or three firms. In the following, we will first consider the simple case of perfect competition among the RES-E equipment producers. We will then work out the differences arising from the more complex case of quantity (Cournot) competition in the upstream market.

1.4.1 Perfect competition in the RES-E equipment market

We anticipate optimal decentralizing policies from the beginning by assuming the conventional firms to be subject to an emission tax τ_t in both periods and the RES-E equipment producers to receive an output subsidy σ_1 in the first period. Since emissions are proportional to output, the emission tax τ_t can also be interpreted as an output tax.

The profits of the clean electricity producers (c), the conventional electricity firms (f), and the RES-E equipment producers (e) are given by

$$\pi^c(q_t(\tilde{x}), \tilde{x}) = P_t(Q_t)q_t(\tilde{x}) - C^t(q_t(\tilde{x}), \tilde{x}) - b_t, \quad t = 1, 2, \quad \tilde{x} \in [0, X_t], \quad (1.10)$$

$$\pi^f(k_t) = P_t(Q_t)k_t - K_t(k_t) - \tau_t k_t, \quad t = 1, 2, \quad (1.11)$$

$$\pi^e(y_1, y_2) = [b_1 + \sigma_1]y_1 - \Gamma^1(y_1) + \delta[b_2 y_2 - \Gamma^2(y_2, L)]. \quad (1.12)$$

1.4 Optimal policy

Here b_t represents the competitive price for RES-E equipment. The first-order condition for profit maximization of the clean electricity producers is then

$$P_t(Q_t) - C_q^t(q_t(\tilde{x}), \tilde{x}) = 0, \quad t = 1, 2. \quad (1.13)$$

The marginal firm X_t in the RES-E equipment sector is determined by the following free-entry zero-profit condition:

$$P_t(Q_t)q_t(X_t) - C^t(q_t(X_t), X_t) - b_t = 0, \quad t = 1, 2, \quad (1.14)$$

while all intra-marginal firms make positive profits. In equilibrium, the fossil-fuel utilities take the output levels of their conventional competitors and the RES-E generators as given. For simplicity we assume that the conventional firms do not take into account possible strategic effects on the producers of RES-E equipment. In principle, they could bring down demand for RES-E equipment and thus the learning effects for the equipment producers by increasing their output in the first period. However, since the market share of electricity generated by renewable sources is still small in most countries, we neglect this strategic consideration. Therefore the behavioral condition of the conventional firms is given by

$$P_t(Q_t) + P_t'(Q_t)k_t - K_t'(k_t) - \tau_t = 0, \quad t = 1, 2. \quad (1.15)$$

Equations (1.14) and (1.15) together determine the aggregate output level of electricity. The behavior of the RES-E equipment producers in the first and second period is governed by the following two conditions:

$$b_1 + \sigma_1 - \Gamma_{y_1}^1(y_1) - \delta\Gamma_L^2(y_2, L) = 0, \quad (1.16)$$

$$b_2 - \Gamma_{y_2}^2(y_2, L) = 0. \quad (1.17)$$

According to 1.16, the RES-E equipment firms only take into account their private learning effects when taking their output decisions but neglect the learning spillovers. We are now ready to define the optimal levels for the policy instruments in obtaining the first-best solution. Equating the first-order conditions for a welfare maximum with the first-order conditions for a profit maximum by the firms and

solving for the policy instruments yields

$$\tau_t^* = P'(Q_t^*)k_t^* + D'_t(mk_t^*), \quad t = 1, 2, \quad (1.18)$$

$$\sigma_1^* = -\delta(n-1)\varepsilon\Gamma_L^2(y_2^*, L^*). \quad (1.19)$$

The optimal tax in both periods corrects for the marginal damage caused by pollution and the low level of output due to oligopolistic competition in the fossil-fuel industry. Accordingly, it is possible for the optimal tax rate to become negative if $|P'(Q_t^*)k_t^*| > D'_t(mk_t^*)$. The optimal output subsidy for RES-E equipment producers in $t = 1$ accounts for the individually neglected learning spill-overs imposed on the other $(n - 1)$ firms. We can summarize our results as follows:

Proposition 1 *Consider an electricity market with Cournot competition among polluting utilities, a competitive fringe of electricity suppliers using renewable energy, and a competitive upstream market of RES-E equipment producers. If emissions are proportional to output, the first-best allocation can be decentralized by imposing a tax on emissions (or output) correcting for both the externality of pollution and the output contraction due to oligopoly power and by paying a subsidy on RES-E equipment correcting for insufficient public learning. The emission tax and the subsidy follow the rules (1.18) and (1.19), respectively.*

If emissions are not proportional to output, but firms have a separate abatement technology, the emission tax will only correct for the pollution and a separate output subsidy would be necessary to correct for the output contraction.

1.4.1.1 The impact of market concentration in the fossil-fuel industry

In this section we will analyze the impact of increasing competition in the fossil-fuel industry on output, prices, and the policy instruments. For this purpose, we compute the comparative-static effects of increasing the number of fossil-fuel utilities m by differentiating (1.2)–(1.4) and (1.13)–(1.19) with respect to m and solving the resulting system of equations for the endogenous variables.⁶ Clearly, a higher number of fossil-fuel firms decreases the market share of the single utilities and increases the total production of fossil-fuel based electricity. As there is less

⁶The proof is provided in Appendix A.1.

strategic output contraction and higher pollution, the optimal tax rate τ_t will increase in both periods:

$$\frac{\partial k_t}{\partial m} < 0, \quad \frac{\partial Q_t^f}{\partial m} > 0, \quad \frac{\partial \tau_t}{\partial m} > 0, \quad t = 1, 2.$$

Moreover, the electricity generated by the marginal renewable electricity producer decreases, so that some green electricity is crowded out of the market:

$$\frac{\partial q_t(X_t)}{\partial m} < 0, \quad \frac{\partial Q^c}{\partial m} < 0, \quad t = 1, 2.$$

In contrast to what is often claimed in the public debate, green electricity providers gain from market power and market concentration in the conventional utility sector. Overall electricity production from dirty and green firms increases, and the price for electricity decreases accordingly:

$$\frac{\partial Q_t}{\partial m} > 0, \quad \frac{\partial p_t}{\partial m} < 0, \quad t = 1, 2.$$

The crowding-out effect on green electricity production decreases the RES-E generators' willingness to pay for RES-E equipment units, so both individual and aggregate RES-E equipment production decreases, together with the RES-E equipment price:

$$\frac{\partial y_t}{\partial m} < 0, \quad \frac{\partial X_t}{\partial m} < 0, \quad \frac{\partial b_t}{\partial m} < 0, \quad t = 1, 2.$$

The sign of the subsidy rate's variation in response to market concentration is ambiguous, so the optimal subsidy policy response to an increasing number of fossil fuel firms is not straightforward. In order to illustrate this ambiguity, we construct a numerical example where the optimal subsidy rate either increases or decreases depending on how strongly the RES-E equipment producers costs are reduced through learning.⁷ A possible interpretation could be as follows: Since the subsidy internalizes the learning spill-overs neglected by the RES-E equipment firms, decreasing output of RES-E equipment leads to a decrease in learning and learning spill-overs, resulting in a lower optimal subsidy rate. If, by contrast,

⁷The numerical example is described in Appendix A.2.

learning by doing leads to a relatively large reduction of production costs in the RES-E equipment industry, it is socially optimal to increase the subsidy rate in order to prevent more crowding-out of RES-E equipment production.

1.4.2 Market power in the RES-E equipment industry

If there is oligopolistic (Cournot) competition in the RES-E equipment sector, an inverse demand function for RES-E equipment has to be defined. This can be derived from the zero-profit condition for RES-E producers:

$$B_t(X_t) = P_t(Q_t)q_t(X_t) - C^t(q_t(X_t), X_t). \quad (1.20)$$

The marginal renewable electricity producers' willingness to pay for one RES-E equipment unit is exactly $B_t(X_t)$. If the RES-E equipment producers notice their market power, they will produce less than optimal. Thus an optimal subsidy on output not only corrects for the neglected learning spill-overs but also for the output contraction. In order to achieve a first-best allocation a subsidy must be paid in both periods. We can thus write the profit of the RES-E equipment producers as follows:

$$\pi^E(y_1, y_2) = [B_1(X_1) + \sigma_1]y_1 - \Gamma^1(y_1) + \delta [[B_2(X_2) + \sigma_2]y_2 - \Gamma^2(y_2, L)]. \quad (1.21)$$

As the number of RES-E equipment producers is exogenous and they engage in oligopolistic competition, their behavior in a symmetric equilibrium is governed by the following conditions for the first and the second period, respectively:

$$B_1(X_1) + B'_1(X_1)y_1 + \sigma_1 - \Gamma^1_{y_1}(y_1) + \delta \left[B'_2(X_2)(n-1) \frac{\partial \tilde{y}_2}{\partial y_1} - \Gamma^2_L(y_2, L) \right] = 0, \quad (1.22)$$

$$B_2(X_2) + B'_2(X_2)y_2 + \sigma_2 - \Gamma^2_{y_2}(y_2; L) = 0. \quad (1.23)$$

In equation (1.22), $\partial \tilde{y}_2 / \partial y_1$ represents the other firms' output contraction (expansion) in $t = 2$ as a reaction on a particular firm's output expansion in $t = 1$. This is the typical effect of shifting the reaction curves outwards in the second period through investment in the first one (Dixit, 1980). Thus the normal reaction is

$\partial \tilde{y}_2 / \partial y_1 < 0$, which in fact happens if ε is not too large.⁸ We are now ready to derive the optimal level of the subsidy rates in both periods:

$$\sigma_1^* = -B_1'(X_1^*)y_1^* - \delta \left[B_2'(X_2^*)(n-1) \frac{\partial \tilde{y}_2^*}{\partial y_1^*} + (n-1)\varepsilon \Gamma_L^2(y_2^*, L^*) \right], \quad (1.24)$$

$$\sigma_2^* = -B_2'(X_2^*)y_2^*. \quad (1.25)$$

The optimal subsidy for RES-E equipment producers in the first period is now composed of three terms. The first term corrects for the output contraction due to oligopolistic competition. This effect is mitigated by the second term representing the strategic output expansion of the firms in the first period. The third term in (1.24) corrects for the learning spill-overs in the same way as described in Section 1.4.1. In the second period, the optimal subsidy only corrects for the output contraction due to oligopolistic competition. Therefore, the subsidy is equal to zero when the RES-E equipment sector is competitive. We summarize the results in the following proposition:

Proposition 2 *Consider an electricity market as described before, except that now there is Cournot competition on the market for RES-E equipment. The first-best allocation can then be decentralized by imposing a tax on emissions (or output) and by paying two different subsidy rates for RES-E equipment production. In period 1 the subsidy corrects for insufficient public learning and strategic behavior by RES-E equipment producers. In period 2 the subsidy only corrects for insufficient output of RES-E equipment. The optimal subsidy rates are given by (1.24) and (1.25), respectively.*

1.4.2.1 The impact of market concentration in the RES-E equipment industry

In the following, we will analyze the impact of market structure on output, prices, and the policy instruments when there is oligopolistic competition in both the fossil-fuel industry and the RES-E equipment sector. For this purpose we conduct comparative-static analysis with respect to the number of fossil-fuel firms m and

⁸If ε is sufficiently large, the reaction is ambiguous. The reason is that the other firms gain in a similar way from experience of the firm that increases its output in the first period. For the derivation of $\partial \tilde{y}_2 / \partial y_1$, please consult Appendix A.3.

the number of RES-E equipment firms n , respectively.⁹ In order to unambiguously sign the comparative-static effects, we assume both the learning spill-over coefficient ε and the strategic cross-period effect $\partial\tilde{y}_2/\partial y_1$ to be equal to zero. This simplification does not imply major drawbacks for the interpretation of our results since by continuity the results must also hold for small values of ε and $\partial\tilde{y}_2/\partial y_1$.

We first analyze the impact of changes in market structure in the conventional industry by differentiating equations (1.2) – (1.4), (1.13)–(1.15), (1.18), (1.20), and (1.22) – (1.25) with respect to the number of fossil-fuel utilities m and solving the resulting system of equations for the endogenous variables. Since the signs of the comparative-static effects are consistent with those summarized in Section 1.4.1.1 and to save on space, we do not repeat them here. In addition, now the sign of the variation of the subsidy paid to the RES-E equipment producers is negative in both periods, implying that subsidies decrease in response to increasing competition in the fossil fuel industry:

$$\frac{\partial\sigma_t}{\partial m} < 0, \quad t = 1, 2.$$

Since we neglected the learning spill-overs and the strategic cross-period effect $\partial\tilde{y}_2/\partial y_1$ in the RES-E equipment industry, the decrease in the subsidy rate can be attributed to the decreasing production of RES-E equipment, leading to smaller output contraction by the RES-E equipment firms.

We now turn to the comparative-static effects of the number of firms in the RES-E equipment industry. Clearly, the higher degree of competition in the RES-E equipment sector decreases the individual output level of a typical RES-E equipment firm but enhances the aggregate output of RES-E equipment and thus dampens the market price for RES-E equipment:

$$\frac{\partial y_t}{\partial n} < 0, \quad \frac{\partial X_t}{\partial n} > 0, \quad \frac{\partial b_t}{\partial n} < 0, \quad t = 1, 2.$$

The overall output of electricity also increases in both periods and leads to decreasing electricity prices, whereas the individual output levels of both the

⁹The proofs are described in Appendix A.4.

fossil-fuel firms and the marginal renewable electricity producer decrease:

$$\frac{\partial Q_t}{\partial n} > 0, \quad \frac{\partial p_t}{\partial n} < 0, \quad \frac{\partial q_t(X_t)}{\partial n} < 0, \quad \frac{\partial k_t}{\partial n} < 0, \quad t = 1, 2.$$

The reason for this result is that declining RES-E equipment prices enable more renewable electricity producers to enter the market, thus crowding out fossil-fuel based electricity production. The crowding-out effect on conventional electricity in turn explains the decline in the emission tax rate:

$$\frac{\partial \tau_t}{\partial n} < 0, \quad t = 1, 2.$$

Again, we cannot unambiguously sign the impact of the number of RES-E equipment firms on the subsidy rates without imposing further assumptions on the cost functions in the RES-E sector. We thus simplify by assuming the effects of learning by doing on the cost of RES-E equipment producers to be close to zero, i.e. $\Gamma_{LL}^2 \approx 0$ and $\Gamma_{Ly_2}^2 \approx 0$. The signs of the comparative-static effects then depend on the rates of change of the marginal costs of both RES-E equipment producers and RES-E generators, i.e. the second derivative of the RES-E equipment producers' cost function with respect to output and the second derivative of the RES-E generators' cost function with respect to the location parameter. Therefore, if $C_{X_t X_t}^t$ and $\Gamma_{y_t y_t}^t$ in $t = 1, 2$ are sufficiently small, we can sign the impact of market structure in the RES-E equipment industry on the subsidy rates as follows:¹⁰

$$\frac{\partial \sigma_t}{\partial n} < 0, \quad t = 1, 2.$$

The economic intuition for the latter result is that stronger competition in the RES-E equipment industry leads to decreasing subsidy rates for RES-E equipment producers, because there is less market power and thus smaller incentives for strategic output contraction.

¹⁰For the RES-E generators, the assumption on the cost function implies that marginal costs are not allowed to increase too steeply when the location of their installations becomes less favorable.

1.5 Feed-in tariffs

We will now consider a situation where first-best policy instruments are not feasible. Instead, we analyze feed-in tariffs as currently implemented in many European and other OECD countries. Under a feed-in tariff policy generators of renewable electricity receive a fixed price ζ_t (which may vary across periods) per unit of electricity fed into the electricity grid. Although in some countries, such as Germany, the fossil-fuel utilities have to pay these tariffs to the RES-E generators according to their share of the market, we here reproduce the Dutch and Danish system where the tariffs are paid by the government. The reason for choosing this approach is that payment of feed-in tariffs by the fossil-fuel utilities may induce further strategic behavior by these firms with respect to their market shares.¹¹ However, as long as the market share of RES-E firms is small, these effects are likely to be small. Moreover, we assume that firms in the conventional sector pay an exogenously given emission (or output) tax τ_t , which may deviate from the first-best tax level. Under this policy regime the firms' profits are given by the following expressions:

$$\pi^F(k_t) = [P_t(Q_t) - \tau_t]k_t - K_t(k_t), \quad t = 1, 2, \quad (1.26)$$

$$\pi^E(y_1, y_2) = b_1 y_1 - \Gamma^1(y_1) + \delta[b_2 y_2 - \Gamma^2(y_2, L)], \quad (1.27)$$

$$\pi^G(q_t(\tilde{x}), \tilde{x}, \zeta_t) = \zeta_t q_t(\tilde{x}) - C^t(q_t(\tilde{x}), \tilde{x}) - b_t, \quad t = 1, 2. \quad (1.28)$$

With perfect competition in the RES-E equipment sector the first-order conditions for profit maximization by the firms are given by

$$P'_t(Q_t)k_t + P_t(Q_t) - \tau_t - K'_t(k_t) = 0, \quad t = 1, 2, \quad (1.29)$$

$$b_1 - \Gamma^1_{y_1}(y_1) - \delta\Gamma^2_L(y_2, L) = 0, \quad (1.30)$$

$$b_2 - \Gamma^2_{y_2}(y_2, L) = 0, \quad (1.31)$$

$$\zeta_t - C^t_{q_t}(q_t, \tilde{x}) = 0, \quad t = 1, 2. \quad (1.32)$$

¹¹See Gersbach & Requate (2004) on modeling strategic behavior when emission taxes are reimbursed according to market share.

The free-entry zero-profit condition for RES-E generators yields

$$\zeta_t q_t(X_t) - C^t(q_t, X_t) - b_t = 0, \quad t = 1, 2. \quad (1.33)$$

With oligopolistic competition in both the fossil-fuel and the RES-E equipment sector the first-order conditions for the RES-E equipment producers yield

$$B^1(X_1, \zeta_1) + B_{X_1}^1(X_1, \zeta_1)y_1 - \Gamma_{y_1}^1(y_1) + \delta[B_{X_2}^2(X_2, \zeta_2)(n-1)\frac{\partial \tilde{y}_2}{\partial y_1} - \Gamma_L^2(y_2, L)] = 0 \quad (1.34)$$

$$B^2(X_2, \zeta_2) + B_{X_2}^2(X_2, \zeta_2)y_2 - \Gamma_{y_2}^2(y_2, L) = 0, \quad (1.35)$$

where the demand for RES-E equipment units $B_t(X_t, \zeta_t)$ is again defined by the free-entry condition for RES-E generators.

1.5.1 Second-best-optimal feed-in tariffs

We will now study the structure of a second-best optimal feed-in tariff given that emission taxes are fixed and possibly non-optimal. For this purpose we therefore consider all the endogenous variables y_t , $q_t(\tilde{x})$, k_t in $t = 1, 2$ and welfare given by equation (1.5) as functions of the feed-in-tariff rates ζ_1 and ζ_2 .

As is always the case under a second-best analysis, the second-best formulas for the policy instruments will contain the reactions of the firms' choice variables on increasing feed-in-tariff rates ζ_1 and ζ_2 . It is therefore useful to briefly study the signs of these effects:¹²

Lemma 1 *With oligopolistic competition in the fossil-fuel industry and perfect competition in the RES-E equipment sector increasing the feed-in tariff for RES-E generators in period $t = 1, 2$ yields: $\frac{\partial q_t(\tilde{x})}{\partial \zeta_t} > 0$, $\frac{\partial k_t}{\partial \zeta_t} < 0$, $\frac{\partial X_t}{\partial \zeta_t} > 0$, $\frac{\partial p_t}{\partial \zeta_t} < 0$, $\frac{\partial Q_t}{\partial \zeta_t} > 0$, $\frac{\partial y_t}{\partial \zeta_t} > 0$, $\frac{\partial b_t}{\partial \zeta_t} > 0$, $\frac{\partial q(\tilde{x})_{-t}}{\partial \zeta_t} = 0$, $\frac{\partial k_{-t}}{\partial \zeta_t} < 0$, $\frac{\partial X_{-t}}{\partial \zeta_t} > 0$, $\frac{\partial p_{-t}}{\partial \zeta_t} < 0$, $\frac{\partial Q_{-t}}{\partial \zeta_t} > 0$, $\frac{\partial y_{-t}}{\partial \zeta_t} > 0$, $\frac{\partial b_{-t}}{\partial \zeta_t} < 0$, where " $-t$ " := $3 - t$.*

As expected, increasing the feed-in tariff in one period increases electricity production by the intra-marginal RES-E generators in that period. Since their

¹²The proof is provided in Appendix A.5.

output decision in a particular period only depends on the feed-in tariff paid in that period, increasing the feed-in tariff in one period does not affect the RES-E generators output in the respective other period. Moreover, due to higher feed-in rates, more RES-E producers become competitive, inducing demand for RES-E equipment and production in the RES-E equipment industry to increase. The RES-E equipment price responds to increasing demand by RES-E generators, rising in the period where the feed-in tariff is increased and falling in the respective other period. In addition, higher feed-in tariffs induce a crowding-out effect on conventional electricity production in both periods. The overall impact on electricity production is positive and the electricity price decreases accordingly.

We are now ready to derive the formulas for the second-best optimal feed-in tariff rates ζ_1 and ζ_2 . Differentiating welfare with respect to the feed-in tariffs and inserting the behavioral conditions gives us two symmetric expressions in ζ_1 and ζ_2 .¹³ Solving these for the feed-in-tariff rates yields

$$\begin{aligned} \zeta_1^{pc} = & P_1(Q_1) + [D'_1(mk_1) - \tau_1 + P'_1(Q_1)k_1] \frac{H_2 m \frac{\partial k_1}{\partial \zeta_1} - H_1 m \frac{\partial k_1}{\partial \zeta_2}}{C_2 H_1 - C_1 H_2} \\ & - \delta \Gamma_L^2 (n-1) \epsilon \frac{H_1 n \frac{\partial y_1}{\partial \zeta_2} - H_2 n \frac{\partial y_1}{\partial \zeta_1}}{C_2 H_1 - C_1 H_2} \\ & + \delta [D'_2(mk_2) - \tau_2 + P'_2(Q_2)k_2] \frac{H_2 m \frac{\partial k_2}{\partial \zeta_1} - H_1 m \frac{\partial k_2}{\partial \zeta_2}}{C_2 H_1 - C_1 H_2}, \end{aligned} \quad (1.36)$$

$$\begin{aligned} \zeta_2^{pc} = & P_2(Q_2) + [D'_2(mk_2) - \tau_2 + P'_2(Q_2)k_2] \frac{C_2 m \frac{\partial k_2}{\partial \zeta_1} - C_1 m \frac{\partial k_2}{\partial \zeta_2}}{[C_1 H_2 - C_2 H_1]} \\ & - [\Gamma_L^2 (n-1) \epsilon] \frac{C_1 n \frac{\partial y_1}{\partial \zeta_2} - C_2 n \frac{\partial y_1}{\partial \zeta_1}}{[C_1 H_2 - C_2 H_1]} \\ & + \frac{1}{\delta} [D'_1(mk_1) - \tau_1 + P'_1(Q_1)k_1] \frac{C_2 m \frac{\partial k_1}{\partial \zeta_1} - C_1 m \frac{\partial k_1}{\partial \zeta_2}}{[C_1 H_2 - C_2 H_1]}, \end{aligned} \quad (1.37)$$

where the superscript "pc" denotes perfect competition in the RES-E equipment sector and C_1 , C_2 , H_1 , and H_2 describe the reaction of clean electricity production when the feed-in-tariff rate changes in a particular period, i.e. $C_1 = q_1(X_1) \frac{\partial X_1}{\partial \zeta_1} +$

¹³The derivation of the second-best optimal feed-in tariffs is provided in Appendix A.6.

$$\frac{\partial Q_1^c}{\partial \zeta_1}, C_2 = q_1(X_1) \frac{\partial X_1}{\partial \zeta_2}, H_1 = q_2(X_2) \frac{\partial X_2}{\partial \zeta_1}, H_2 = q_2(X_2) \frac{\partial X_2}{\partial \zeta_2} + \frac{\partial Q_2^c}{\partial \zeta_2}.$$

As can be seen from (1.36) and (1.37), the second-best optimal feed-in tariffs consist of the electricity price in the respective period $t = 1, 2$, plus a mark-up that takes into account (i) the marginal pollution damage from fossil-fuel based electricity production, (ii) the strategic effects in the oligopolistic fossil-fuel industry, and (iii) the learning spill-overs in the RES-E equipment industry.

Each of the three parts of the mark-up terms in (1.36) and (1.37), respectively, is multiplied by a weighting factor containing the comparative-static effects with respect to the feed-in tariffs derived at the beginning of this section. Unfortunately, since the indirect effects of increasing the feed-in tariff in one period on output in the respective other period do not vanish, the signs of the second-best feed-in tariffs cannot be unambiguously determined. However, our numerical calculations suggest that the indirect effects are likely to be small. Accordingly, we will assume in the following that the direct effects dominate the indirect effects, i.e. $\frac{\partial k_t}{\partial \zeta_t} > \frac{\partial k_t}{\partial \zeta_{-t}}, \frac{\partial y_t}{\partial \zeta_t} > \frac{\partial y_t}{\partial \zeta_{-t}}$, and $\frac{\partial X_t}{\partial \zeta_t} > \frac{\partial X_t}{\partial \zeta_{-t}}$. This assumption enables us to interpret the composition of the second-best optimal feed-in tariffs in a straightforward fashion. For brevity, we focus on the interpretation of ζ_1 , but the interpretation of ζ_2 is similar.

Following our assumption concerning the magnitude of the comparative-static effects, the weighting factor of the first mark-up term in (1.36) is positive. This implies that if the tax rate falls short of (exceeds) marginal damage, provided that the strategic output contraction of the fossil-fuel utilities is not too large, this will have a positive (negative) impact on the feed-in-tariff rate, i.e. the feed-in tariff paid to the renewable electricity generators will lie above (below) the market price for electricity. Similarly, if output contraction due to oligopolistic competition in the fossil-fuel industry is very large, the second-best optimal feed-in-tariff rate will be reduced. The weighting factor of the second mark-up term in (1.36) is also positive, implying that the existence of learning spill-overs in the RES-E equipment industry will have a positive effect on the feed-in tariff in the first period. If learning is purely private, the second term vanishes and the feed-in tariff will only correct for environmental damage and distortions in the fossil-fuel industry. The sign of the third mark-up term in (1.36) relating to the second-period effects in the fossil-fuel industry is ambiguous since the weighting

factor can be either positive or negative. If the weighting factor is *positive* and the emission tax in $t = 2$ falls short of marginal damage, or if the weighting factor is *negative* and the emission tax in $t = 2$ exceeds marginal damage, the third term will further raise the feed-in tariff in $t = 1$ (provided the strategic output contraction is not too large). The intuition for this effect is that the regulator anticipates that fossil-fuel utilities might shift their production to $t = 1$ when facing high emission taxes in $t = 2$. Therefore, in order to mitigate this reaction, the regulator increases the feed-in tariff in $t = 1$. However, compared to the first two (direct) effects the impact of the third mark-up term on the feed-in-tariff rate is likely to be small. We can summarize the results as follows:

Proposition 3 *Consider an electricity market as described above and perfect competition among RES-E equipment producers. Assume an exogenous, possibly non-optimal tax is imposed on emissions. In each period the second-best optimal feed-in tariff is equal to the market price for electricity plus a term that corrects for the difference between marginal damage and the emission tax rate, the output contraction of fossil-fuel utilities and insufficient learning spill-overs, taking into account the firms' reactions on the feed-in tariffs. The second-best optimal feed-in-tariff rates are given by (1.36) and (1.37), respectively.*

In the case of oligopolistic competition in both the fossil-fuel and the RES-E equipment industry, the structure of the second-best optimal feed-in tariff becomes a bit more complex as it also takes into account the strategic effects in the RES-E equipment sector. Using the same techniques as for the derivation of (1.36) and (1.37) we arrive at the following feed-in-tariff rates:

$$\begin{aligned}
 \zeta_1^{oc} = & P_1(Q_1) + [D_1'(mk_1) - \tau_1 + P_1'(Q_1)k_1] \frac{H_2 m \frac{\partial k_1}{\partial \zeta_1} - H_1 m \frac{\partial k_1}{\partial \zeta_2}}{C_2 H_1 - C_1 H_2} \\
 & - \left[B_{X_1}^1(X_1, \zeta_1) y_1 + \delta B_{X_2}^2(X_2, \zeta_2) (n-1) \frac{\partial \tilde{y}_2}{\partial y_1} \right. \\
 & \left. + \delta \Gamma_L^2(n-1) \epsilon \right] \frac{H_1 n \frac{\partial y_1}{\partial \zeta_2} - H_2 n \frac{\partial y_1}{\partial \zeta_1}}{C_2 H_1 - C_1 H_2} \\
 & + \delta [D_2'(mk_2) - \tau_2 + P_2'(Q_2)k_2] \frac{H_2 m \frac{\partial k_2}{\partial \zeta_1} - H_1 m \frac{\partial k_2}{\partial \zeta_2}}{C_2 H_1 - C_1 H_2} \\
 & - \delta B_{X_2}^2(X_2, \zeta_2) y_2 \frac{H_1 n \frac{\partial y_2}{\partial \zeta_2} - H_2 n \frac{\partial y_2}{\partial \zeta_1}}{C_2 H_1 - C_1 H_2},
 \end{aligned} \tag{1.38}$$

$$\begin{aligned}
 \zeta_2^{oc} = & [D'_2(mk_2) - \tau_2 + P'_2(Q_2)k_2] \frac{C_2m \frac{\partial k_2}{\partial \zeta_1} - C_1m \frac{\partial k_2}{\partial \zeta_2}}{[C_1H_2 - C_2H_1]} \\
 & - B_{X_2}^2(X_2, \zeta_2)y_2 \frac{C_1n \frac{\partial y_2}{\partial \zeta_2} - C_2n \frac{\partial y_2}{\partial \zeta_1}}{[C_1H_2 - C_2H_1]} \\
 & + P_2(Q_2) + [D'_1(mk_1) - \tau_1 + P'_1(Q_1)k_1] \frac{C_2m \frac{\partial k_1}{\partial \zeta_1} - C_1m \frac{\partial k_1}{\partial \zeta_2}}{\delta[C_1H_2 - C_2H_1]} \quad (1.39) \\
 & - \left[B_{X_1}^1(X_1, \zeta_1)y_1 + \delta B_{X_2}^2(X_2, \zeta_2)(n-1) \frac{\partial \tilde{y}_2}{\partial y_1} \right. \\
 & \left. + \delta \Gamma_L^2(n-1)\epsilon \right] \frac{C_1n \frac{\partial y_1}{\partial \zeta_2} - C_2n \frac{\partial y_1}{\partial \zeta_1}}{\delta[C_1H_2 - C_2H_1]},
 \end{aligned}$$

where the superscript "oc" denotes oligopolistic competition in the RES-E equipment sector and C_1 , C_2 , H_1 , and H_2 again denote the reaction of green electricity production when the feed-in tariff rate changes in a particular period. Note that the comparative-static effects of increasing the feed-in tariffs on the endogenous variables with oligopolistic competition in the RES-E equipment industry are in line with Lemma 1.¹⁴ Compared to (1.36) and (1.37), equations (1.38) and (1.39) include an augmented second mark-up term and an additional fourth mark-up term, representing the distortions caused by oligopolistic competition in the RES-E equipment industry.

Assuming again that the direct comparative-static effects dominate the indirect effects, the weighting factor of the augmented second term in (1.38) is positive. This implies that the feed-in tariff in $t = 1$ will increase compared to the case of perfect competition in the RES-E equipment industry as it also accounts for the strategic output contraction by the RES-E equipment firms, i.e. $B_{X_1}^1(X_1, \zeta_1)y_1 < 0$. This effect is mitigated by the fact that RES-E equipment firms want to expand their output in the first period in order to shift their reaction curves outwards in the second, represented by the term $B_{X_2}^2(X_2, \zeta_2)(n-1) \frac{\partial \tilde{y}_2}{\partial y_1} > 0$. Moreover, the fourth term in (1.38) indicates that the feed-in tariff in $t = 1$ also takes into account the strategic output contraction by RES-E equipment firms in the second period. Due to $B_{X_2}^2(X_2, \zeta_2)y_2 < 0$, this will raise the feed-in tariff if

¹⁴Please consult Appendix A.5 for details.

the weighting factor is positive and will decrease the feed-in tariff if the weighting factor is negative.

The composition of ζ_2^{oc} can be interpreted analogously with the predominant effects arising from the third and the fourth mark-up term in (1.39). We therefore summarize the results in the following proposition:

Proposition 4 *Consider an electricity market as described above and oligopolistic competition among RES-E equipment producers and assume an exogenous, possibly non-optimal tax is imposed on emissions. In addition to the components described in Proposition 3, the second-best optimal feed-in tariff in each period then also accounts for the output contraction of RES-E equipment producers. The second-best optimal feed-in-tariff rates are given by (1.38) and (1.39), respectively.*

1.5.2 Welfare comparisons through simulations

In this section we will evaluate the implications of a second-best optimal feed-in-tariff policy on welfare and compare these to the first-best solution. For this purpose, we simultaneously solve the system of equations (1.1)-(1.4) and (1.13)-(1.19) and calculate the social welfare when first-best policies are applied. We also work out the social welfare of a second-best feed-in-tariff policy by simultaneously solving the system of equations (1.1), (1.2), (1.4), (1.29)-(1.37). Following Fischer & Newell (2008) we assume iso-elastic electricity demand and quadratic cost and damage functions, yielding linear electricity supply and linear marginal damage functions (see Table 1.1). Table 1.2 summarizes the parameter values employed in our study, most of which have been adopted from Fischer & Newell (2008).¹⁵ The slope parameter of marginal pollution damage d is consistent with a constant marginal damage of US-\$43 per ton of CO₂ (see Tol, 2005). The learning parameter b is calibrated to induce a learning rate of about 20 percent, which is at the upper limit of most empirical studies (see Junginger *et al.*, 2005).

¹⁵Fischer & Newell (2008) have calibrated their values to simulations that study the electricity market impact of different CO₂ reduction goals taken from the Energy Information Administration's National Energy Modeling System (EIA, 2006).

Table 1.1: Functional forms

Functional form	Description
$C_t(q_t(\tilde{x}), \tilde{x}) = c_1 q_t + \frac{c_2}{2}(q_t + f\tilde{x})^2$	Cost function of the RES-E generators in $t = 1, 2$
$K_t(k_t) = h_1 k_t + \frac{h_2}{2} k_t^2$	Cost function of the fossil-fuel firms in $t = 1, 2$
$\Gamma^1(y_1) = \frac{\gamma}{2} y_1^2$	Cost function of the RES-E equipment producers in $t = 1$
$\Gamma^2(y_2, L) = \frac{\gamma}{4}(y_2 - bL)^2 + \frac{\gamma}{4} y_2^2$	Cost function of the RES-E equipment producers in $t = 2$
$L = y_1 + (n - 1)\varepsilon \tilde{y}_1$	Learning by doing in the RES-E equipment industry in $t = 1$
$D_t(mk_t) = \frac{d}{2}(mk_t)^2$	Pollution damage in $t = 1, 2$
$P_t(Q_t) = Q_t^\alpha$	Electricity demand function in $t = 1, 2$

Table 1.2: Parameter values in the baseline case

Parameter	Base value	Description
α	-4	Elasticity of electricity demand
h_1	0.07	Intercept of fossil-fuel utilities cost function
h_2	$1.8 * 10^{-14}$	Scaling parameter in fossil-fuel utilities cost function
γ, b	0.1, 0.2	Scaling parameters in RES-E equipment producers cost function
c_1	0.1	Intercept of RES-E producers cost function
c_2, f	$1.2 * 10^{-13}, 0.05$	Scaling parameters in RES-E producers cost function
d	0.027	Scaling parameter in pollution damage function
ε	0.5	Learning spill-over coefficient
δ	0.95	Discount rate

For the second-best calculations, we consider three alternative scenarios for the exogenously given emission tax: $\tau_t = 0$ (no emission tax), $\tau_t = \frac{1}{2}\tau_t^*$ (emission tax rate equal to half its first-best value), and $\tau_t = \tau_t^*$ (first-best emission tax).

The results for the cases with perfect and oligopolistic competition in the RES-E equipment industry are displayed in Table 1.3 and Table 1.4, respectively. In each table, the first row displays the percentage differences between optimal welfare and welfare resulting from second-best optimal feed-in tariffs, given certain fixed levels of the emission tax. The results yield two main conclusions. First, when the exogenous emission tax is equal to the first-best level, the welfare loss from a second-best optimal feed-in tariff policy is very small. When the exogenous tax rate falls short of its first-best level, however, the welfare loss is considerably higher. Thus a second-best optimal feed-in tariff is much less efficient than the emission tax in internalizing both the environmental and competition effects in the fossil-fuel industry. Second, in the case of imperfect competition among the

RES-E equipment firms, the welfare losses through second-best optimal feed-in tariffs are even bigger since the feed-in tariffs also have to correct for strategic output contraction in the RES-E equipment sector.

Tables 1.3 and 1.4 also indicate how producer and consumer surplus are affected by the change from first-best to second-best optimal policies. Consistent with the above-mentioned observations on social welfare, the impact of switching from a first-best tax/subsidy policy to a second-best feed-in-tariff policy is much more pronounced when the exogenous emission tax falls short of its first-best level. The renewable electricity and the renewable equipment sector benefit from the introduction of feed-in tariffs compared to a first-best policy, increasing their market shares and surpluses at the expense of fossil-fuel-based electricity producers. The implementation of second-best optimal feed-in tariffs also leads to significant electricity price increases that negatively affect the consumer surplus. Moreover, since dirty electricity is crowded out of the market, second-best optimal feed-in-tariff policies reduce pollution damage. Note that in our calculations the second-best optimal feed-in tariffs lie below the electricity price when the exogenous emission tax falls short of its optimal value. This happens because the strategic effect in the fossil-fuel sector (driven by the inelastic electricity demand) overcompensates both marginal damage and learning spill-overs.

1.5 Feed-in tariffs

Table 1.3: Deviation of different second-best feed-in-tariff policy scenarios relative to a first-best emission tax/learning subsidy policy: Oligopoly in the fossil-fuel industry only

Δ Variable (in %)	FITs with exogenous emission tax $\tau_t = \tau_t^*$	FITs with exogenous emission tax $\tau_t = \frac{1}{2}\tau_t^*$	FITs with exogenous emission tax $\tau_t = 0$
Δ Welfare	-0.00019	-12.8395	-28.3360
Δ Consumer surplus			
t=1	0.00003	-6.6435	-13.3265
t=2	-0.06055	-6.9582	-12.6583
Δ Producer surplus (green electricity)			
t=1	-3.04845	33129.8	60761.2
t=2	-0.93635	27386.2	56470.4
Δ Producer surplus (dirty electricity)			
t=1	-0.00013	-22.3643	-32.3027
t=2	0.24836	-21.0085	-35.0382
Δ Producer surplus (RES-E equipment)			
t=1	-6.4724	9696.1	15631.5
t=2	-0.4688	8812.1	15162.8
Δ Electricity price			
t=1	-0.00017	37.189	77.3519
t=2	0.32540	38.927	73.2385
Δ Total output of green electricity			
t=1	0.00022	3214.13	4660.57
t=2	-0.41655	2869.29	4364.36
Δ Total output of dirty electricity			
t=1	0.00004	-27.6829	-42.480
t=2	-0.07889	-27.6182	-42.822
Δ RES-E equipment price			
t=1	6.3946	988.383	1279.48
t=2	0.2128	837.516	1132.71
Δ Total number of RES-E equipment			
t=1	-2.99688	885.39	1152.45
t=2	-0.51587	848.39	1137.19
Δ Damage			
t=1	0.00008	-47.7023	-66.9146
t=2	-0.15771	-47.6088	-67.3067

1.5 Feed-in tariffs

Table 1.4: Deviation of different second-best feed-in tariff policy scenarios relative to a first-best emission tax/learning subsidy policy: Oligopoly in both the fossil-fuel and the RES-E equipment industry

Δ Variable (in %)	FITs with exogenous emission tax $\tau_t = \tau_t^*$	FITs with exogenous emission tax $\tau_t = \frac{1}{2}\tau_t^*$	FITs with exogenous emission tax $\tau_t = 0$
Δ Welfare	-0.00049	-12.8568	-29.7965
Δ Consumer surplus			
t=1	-0.0844	-6.3105	-13.313
t=2	0.0000	-5.6881	-7.515
Δ Producer surplus (green electricity)			
t=1	-8.4055	33582.7	60067.2
t=2	-0.8523	31630.1	82887.5
Δ Producer surplus (dirty electricity)			
t=1	0.3394	-23.8109	-32.3581
t=2	-0.00006	-26.4725	-56.2294
Δ Producer surplus (RES-E equipment)			
t=1	-53.4453	4702.22	7333.17
t=2	-12.7662	8624.34	18971.9
Δ Electricity price			
t=1	0.44742	0.75797	77.270
t=2	-0.00006	0.10866	42.287
Δ Total output of green electricity			
t=1	-0.5867	-0.9682	4663.3
t=2	-0.00009	-0.1394	5609.2
Δ Total output of dirty electricity			
t=1	-0.1101	-0.18374	-42.487
t=2	0.0000	-0.02638	-46.924
Δ RES-E equipment price			
t=1	11.9904	11.7026	1315.11
t=2	1.7154	1.6489	1431.46
Δ Total number of RES-E equipment			
t=1	-5.9587	-6.19962	1138.29
t=2	-0.8296	-0.93460	1317.91
Δ Damage			
t=1	-0.220	-47.759	-66.923
t=2	0.0000	-47.862	-71.829

1.5.3 The impact of market structure on the size of feed-in tariffs

To investigate the impact of changes in market structure in the conventional electricity sector on the second-best optimal feed-in tariffs, we again consider the numerical example from the previous section and study the impact of market structure (represented by the number of oligopolistic firms) on the second-best optimal feed-in tariffs and market performance.

Figures 1.1, 1.2, and 1.3 illustrate the results for the case of oligopolistic competition in the fossil-fuel industry and perfect competition among RES-E equipment producers assuming an emission tax rate equal to zero. Similar to the comparative-static results described in Section 1.4.1.1, more competition among fossil-fuel utilities leads to an increasing output of fossil-fuel electricity and hence to a decrease in electricity prices. This effect crowds out production of renewable electricity and thus also depresses demand and prices in the RES-E equipment sector. This mechanism is always present.

Interestingly, however, the impact on the second-best optimal level of the feed-in tariffs is less clear. From Figure 1.1 we see that, if the demand elasticity is low ($\epsilon = 1/\alpha = -1/4.0$ and below), the second-best optimal feed-in-tariff rate decreases as electricity markets become more competitive. The reason is that as total output is hardly affected by increasing competition there is no large increase in marginal damage either. Therefore, the dominating effect on the second-best optimal feed-in tariffs is the decrease in electricity prices (first terms in formulas (1.36) and (1.37)). So in the short run (when demand elasticity is low), liberalizing energy markets brings about lower feed-in tariffs, which benefits public budgets and consumers who have to pay less to subsidize renewable energy.

If, by contrast, demand elasticity is relatively high ($\epsilon = 1/\alpha = -1/2.0$ and higher), the second-best optimal feed-in-tariff rate increases as the electricity market becomes more competitive (see Figure 1.2). The intuitive reason is that increased output induces higher emissions and hence higher marginal damage, whereas the strategic output corrective of the feed-in-tariff rate (term $P'_1(Q_1)k_1$ in (1.36) and $P'_2(Q_2)k_2$ in (1.37)) decreases. To counteract this effect, feed-in-tariff rates must be enhanced in both periods. Therefore, liberalizing the electricity

markets has the opposite effect in the long run: (second-best optimal) feed-in tariffs have to be raised, thus offsetting the positive effect of market liberalization for consumers and public budgets. For intermediate values of demand elasticities we obtain a U-shaped relationship between the number of firms and the size of the feed-in tariff (see Figure 1.3).

1.5 Feed-in tariffs

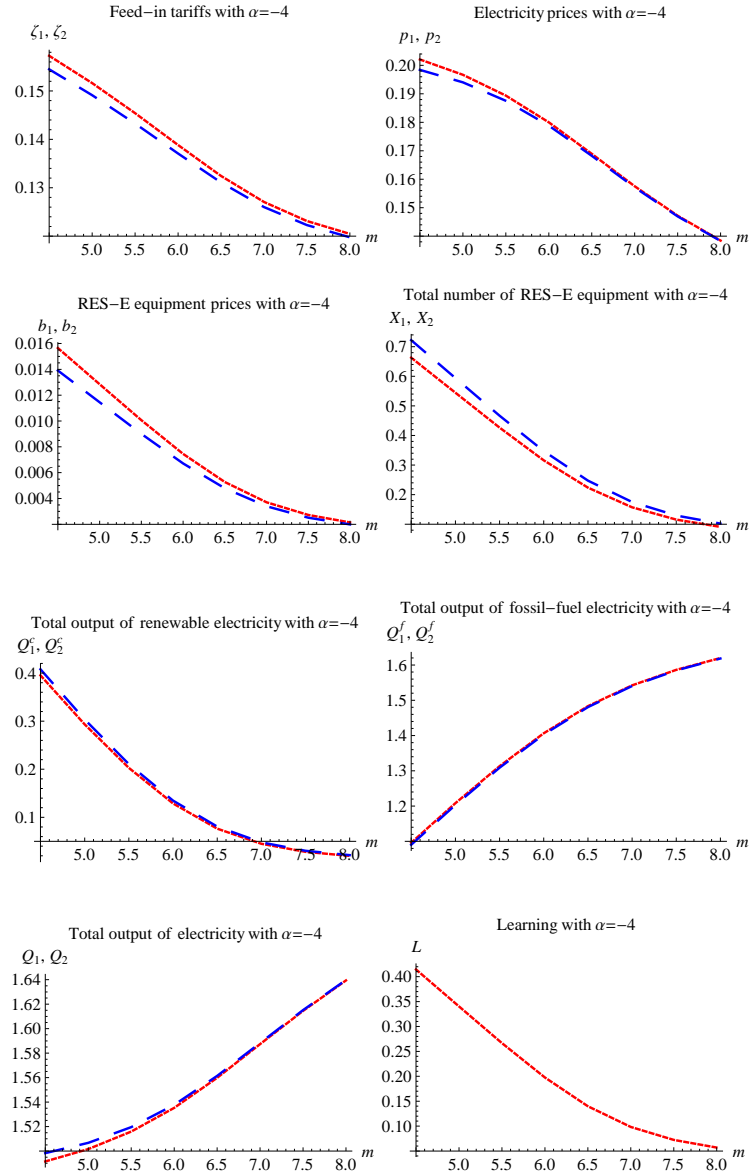


Figure 1.1: Impact of increasing the number of fossil-fuel firms with perfect competition in the RES-E equipment industry and low elasticity of demand (short-[long-]dashed lines for $t = 1$ [$t = 2$]).

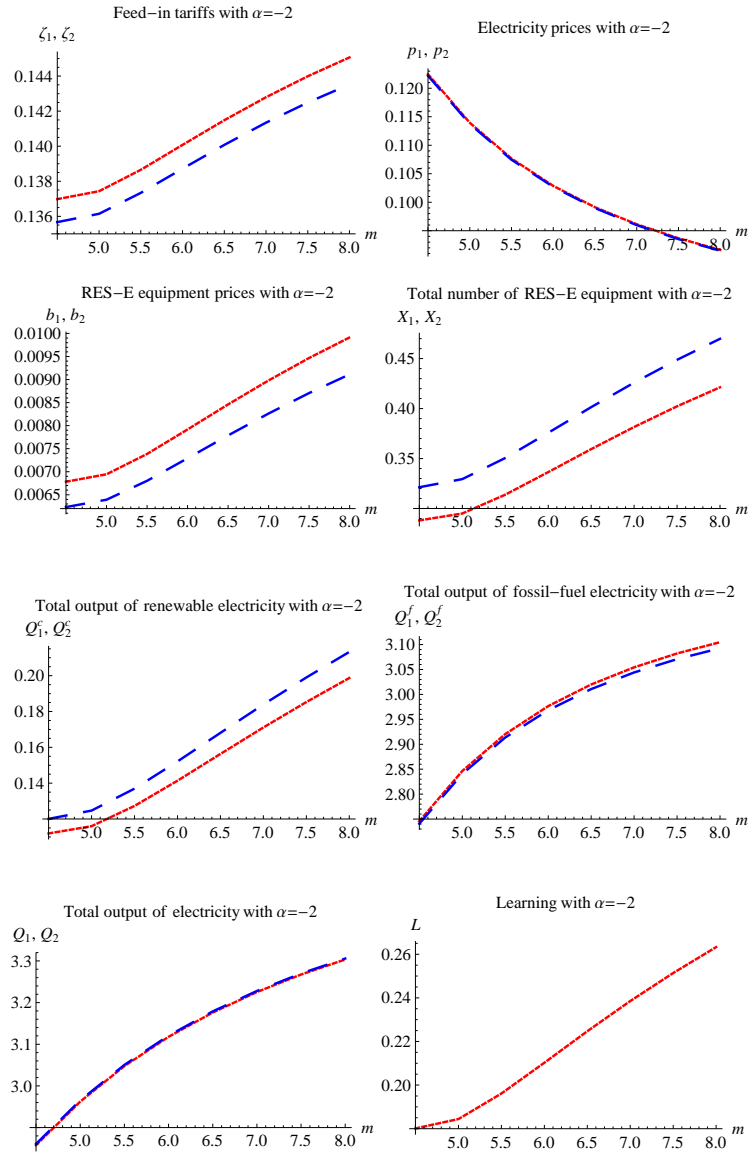


Figure 1.2: Impact of increasing the number of fossil-fuel firms with perfect competition in the RES-E equipment industry and high elasticity of demand (short-[long-]dashed lines for $t = 1$ [$t = 2$]).

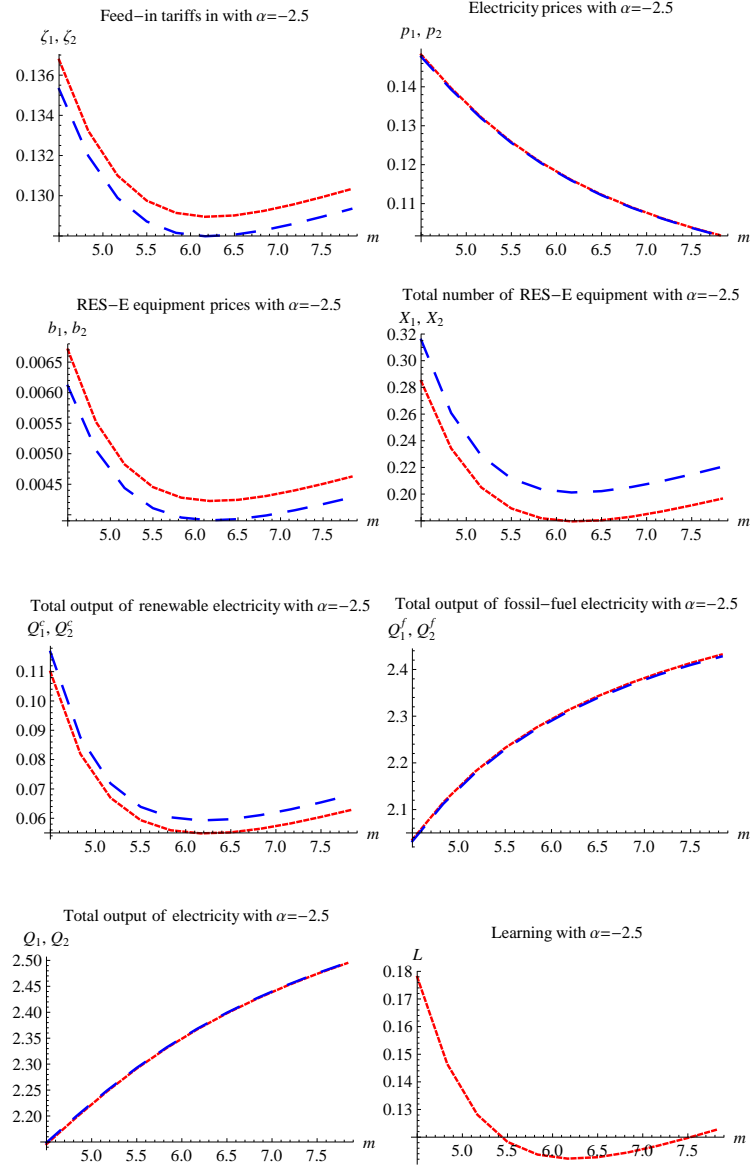


Figure 1.3: Impact of increasing the number of fossil-fuel firms with perfect competition in the RES-E equipment industry and intermediate elasticity of demand (short-[long-]dashed lines for $t = 1$ [$t = 2$]).

In the case of oligopoly power in the RES-E equipment industry the effects of increasing competition in the fossil-fuel sector are qualitatively similar, but differ quantitatively (see Figures 1.4 and 1.5). In general, imperfect competition among RES-E equipment producers induces higher prices and lower production of RES-E equipment, which in turn leads to a lower output of clean electricity. In addition, the second-best optimal feed-in tariffs are higher than in the case of perfect competition since they also internalize the strategic output contraction in the RES-E equipment sector by indirectly subsidizing that market. Another interesting observation concerns the relative size of the feed-in-tariff in the first compared to the second period. When the emission tax fully accounts for the externalities in the fossil-fuel industry we obtain a higher feed-in tariff in the first than in the second period (see Figure 1.5). By contrast, when the emission tax is equal to zero, the feed-in tariff in the second period is higher than in the first period (see Figure 1.4). Therefore, the statement that feed-in-tariffs should decrease over time to account for the learning effects in the RES-E industry does not hold in general.

Finally, Figures 1.6 and 1.7 illustrate the impact of market structure in the RES-E equipment sector. With increasing competition on the market for RES-E equipment, falling RES-E equipment prices trigger more market entry by RES-E operators and both green electricity and total electricity output increase while dirty electricity is crowded out to some extent. The impact on the second-best optimal feed-in-tariff rates is ambiguous, depending on the chosen emission tax level. When the emission tax is equal to zero, the second-best optimal feed-in tariff rates decrease in both periods (see Figure 1.6). The intuitive reason for this result is that negative externalities are reduced in both the RES-E equipment industry (due to smaller oligopolistic output contraction) and in the fossil-fuel industry (due to crowding out of dirty electricity production and thus lower marginal damage). By contrast, when emission taxes are equal to their first-best levels, the second-best optimal feed-in tariff rate increases in the first and decreases in the second period (see Figure 1.7). As the emission tax now fully internalizes all external effects in the fossil-fuel sector, the increasing feed-in tariff in the first period can be explained by the positive externalities of learning spill-overs that are now predominant in the RES-E equipment industry. Since

1.5 Feed-in tariffs

no learning occurs in the second period, the feed-in tariff then decreases due to the declining oligopolistic output contraction of RES-E equipment producers. In addition, similar to the results shown in Figures 1.4 and 1.5, second-best optimal feed-in-tariff rates may be higher in the second than in the first period, again depending on the emission tax level.

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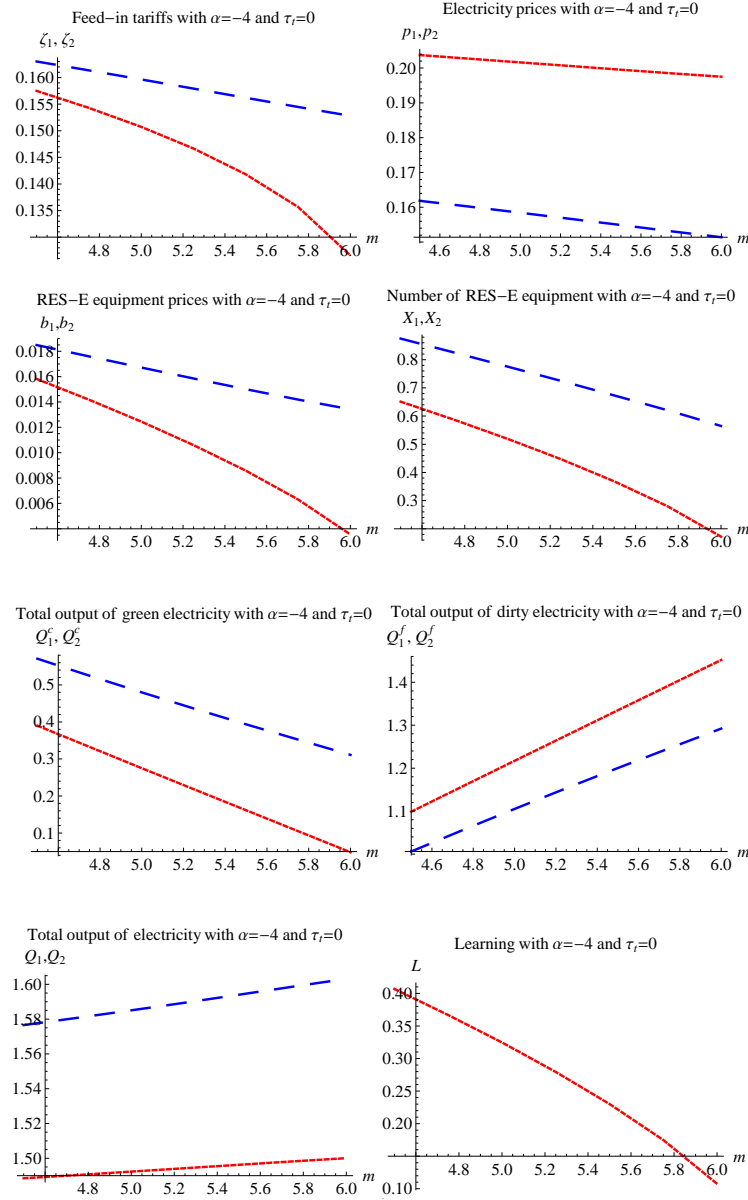


Figure 1.4: Impact of increasing the number of fossil-fuel firms with oligopolistic competition in the RES-E equipment industry and emission taxes equal to zero (short-[long-]dashed lines for $t = 1$ [$t = 2$]).

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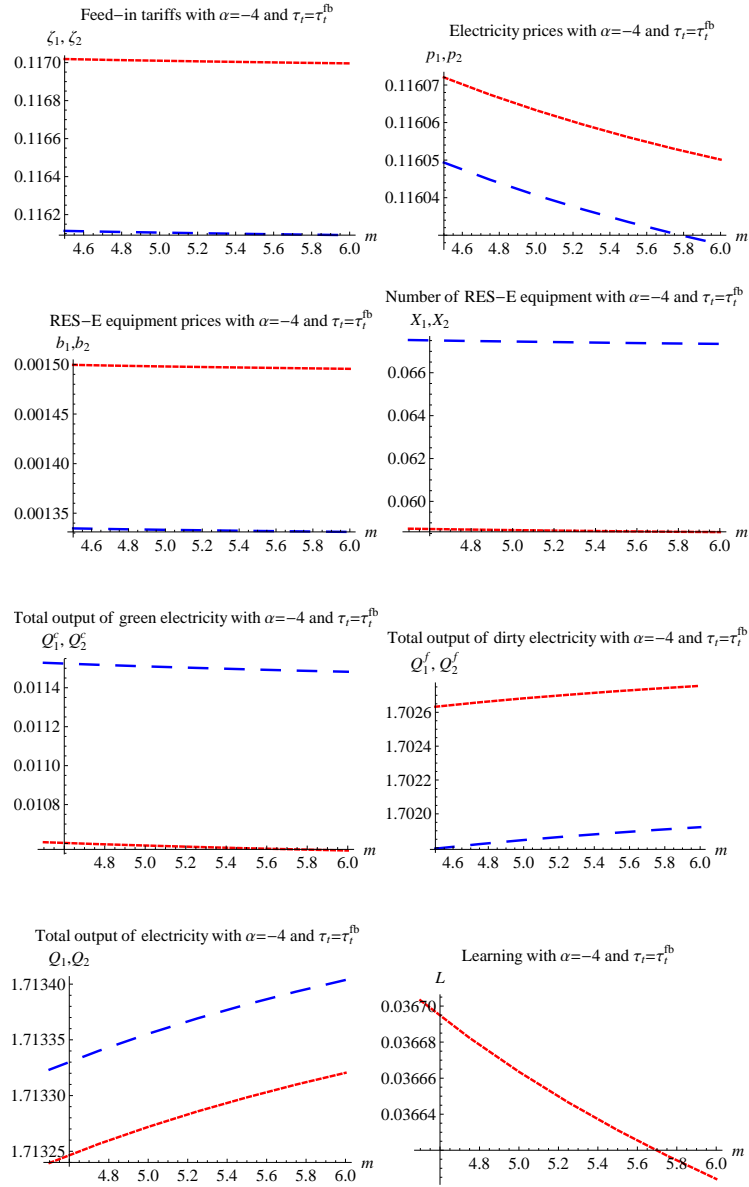


Figure 1.5: Impact of increasing the number of fossil-fuel firms with oligopolistic competition in the RES-E equipment industry and first-best emission taxes (short-[long-]dashed lines for $t = 1$ [$t = 2$]).

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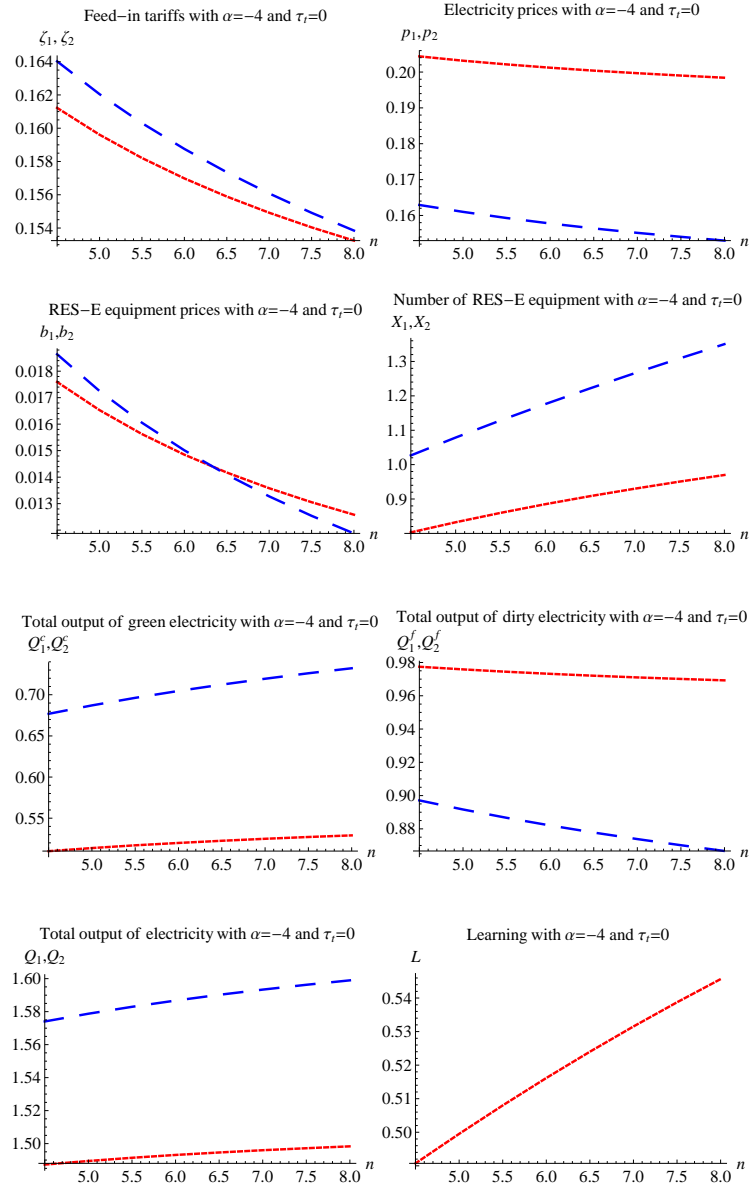


Figure 1.6: Impact of increasing the number of RES-E equipment firms with oligopolistic competition in the RES-E equipment industry and emission taxes equal to zero (short-[long-]dashed lines for $t = 1$ [$t = 2$]).

1.5 Feed-in tariffs

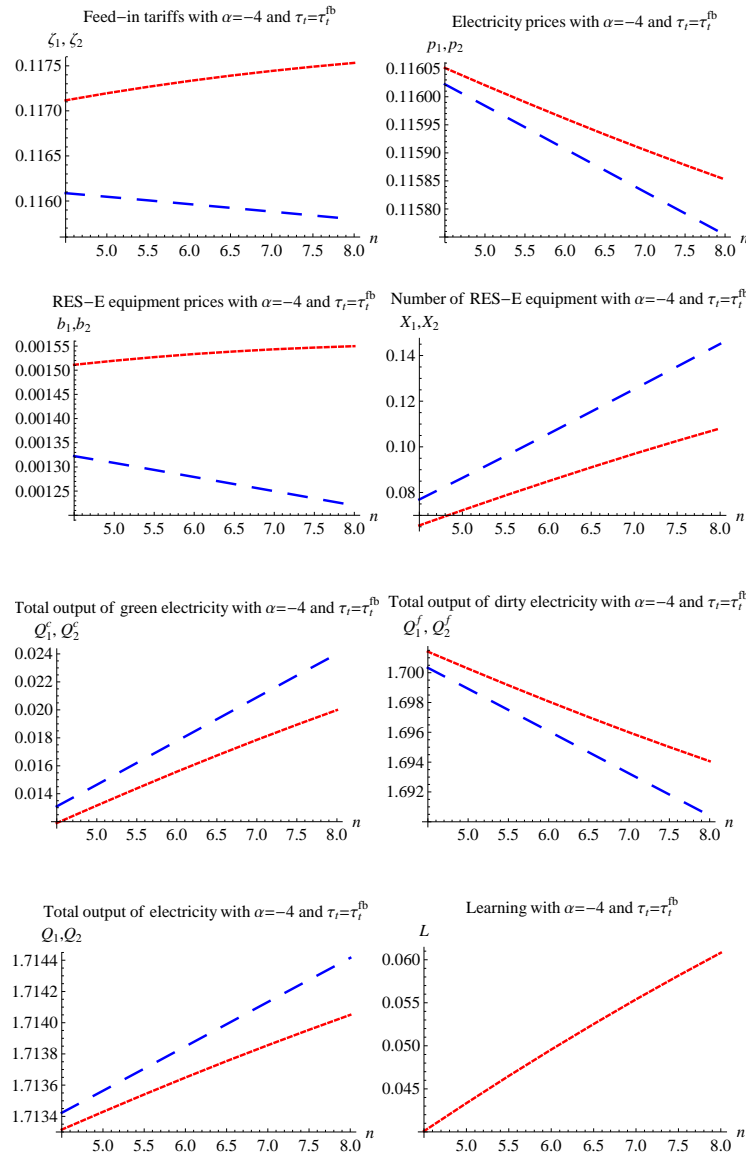


Figure 1.7: Impact of increasing the number of RES-E equipment firms with oligopolistic competition in the RES-E equipment industry and first-best emission taxes (short-[long-]dashed lines for $t = 1$ [$t = 2$]).

1.5.4 Sensitivity analysis

To test the stability of our numerical results we conduct a sensitivity analysis with respect to the parameters determining the degree of learning spill-overs, the magnitude of cost reductions through learning by doing in the RES-E equipment industry, and the elasticity of electricity demand. For brevity, we focus on the impact of these parameters on the welfare differences between first-best and second-best policies. The results for the case of perfect and oligopolistic competition in the RES-E equipment industry are displayed in Table 1.5 and Table 1.6, respectively. In both tables the first line carries forward the results of the baseline case (described in Tables 1.3 and 1.4), respectively, illustrating that in both cases the impact on the relative performance of second-best policies by varying either the ability of firms to learn or the degree of learning spill-overs is rather small.

When the emission tax is not set at its first-best level, a higher learning ability ($b = 0.3$) and complete learning spill-overs ($\varepsilon = 1$) both slightly improve the relative performance of second-best feed-in-tariff policies compared to the baseline scenario. By contrast, a lower learning ability ($b = 0.01$) and no learning spill-overs ($\varepsilon = 0$) both slightly reduce the relative performance of those policies.

By contrast, varying the demand elasticity for electricity leads to fairly large impacts on the relative performance of second-best policies. When demand is more elastic than in the baseline ($\epsilon = 1/\alpha = -1/3.5$)¹⁶, the welfare loss induced by second-best policies relative to optimal welfare is significantly lower. By contrast, less elastic demand than in the baseline ($\epsilon = 1/\alpha = -1/4.5$) leads to a significantly higher welfare loss of second-best optimal feed-in-tariff policies. These results indicate that in our framework of imperfect competition demand elasticity has a much larger impact on policy performance than the parameters relating to the learning effects and spill-overs in the RES-E equipment industry.

¹⁶Recall that α is the elasticity of the *inverse* demand function.

1.6 Concluding remarks

Table 1.5: Sensitivity analysis: Oligopoly in the fossil-fuel industry only

ΔWelfare relative to first best policy (%)	FITs with exog. tax $\tau_t = \tau_t^*$	FITs with exog. tax $\tau_t = \frac{1}{2}\tau_t^*$	FITs with exog. tax $\tau_t = 0$
Baseline	-0.00019	-12.8395	-28.3360
More elastic demand ($\alpha = -3.5$)	-0.00009	-7.13675	-17.0856
Less elastic demand ($\alpha = -4.5$)	-0.19674	-20.3974	-44.0165
High learning ($b = 0.3$)	-0.00068	-12.6169	-27.9531
Low learning ($b = 0.01$)	0.00000	-13.5577	-29.5668
Complete learning spill-overs ($\varepsilon = 1$)	-0.00077	-12.6361	-27.9057
Purely private learning ($\varepsilon = 0$)	0.00000	-13.2521	-29.0426

Table 1.6: Sensitivity analysis: Oligopoly in both the fossil-fuel and the RES-E equipment industry

ΔWelfare relative to first best policy (%)	FITs with exog. tax $\tau_t = \tau_t^*$	FITs with exog. tax $\tau_t = \frac{1}{2}\tau_t^*$	FITs with exog. tax $\tau_t = 0$
Baseline	-0.00049	-12.8568	-29.7965
More elastic demand ($\alpha = -3.5$)	-0.00887	-7.16979	-18.0884
Less elastic demand ($\alpha = -4.5$)	-0.67618	-20.3506	-44.5619
High learning ($b = 0.3$)	-0.000718	-12.6247	-29.3786
Low learning ($b = 0.01$)	0.00000	-13.58	-31.4121
Complete learning spill-overs ($\varepsilon = 1$)	-0.21601	-12.5984	-29.324
Purely private learning ($\varepsilon = 0$)	-0.14676	-13.2663	-30.5291

1.6 Concluding remarks

In this chapter we have set up a model to investigate the performance of subsidy policies for employing renewable energy sources in electricity production such as wind or photovoltaic power. As the existence of learning by doing and learning spill-overs is one of the most prominent arguments advanced by policy makers in favor of such subsidies, we have explicitly accounted for these effects by consid-

ering an RES-E equipment industry that benefits from cost reductions through private and public learning. We find that the regulator can obtain the first-best allocation by implementing a tax on emissions and an output subsidy for RES-E equipment producers. The optimal tax is characterized by two counteracting components. It internalizes the externalities of emissions but also corrects for the strategic output contraction by the oligopolistic fossil-fuel firms. The output subsidy for RES-E equipment producers accounts for the learning spill-overs and, in the case of an oligopolistic RES-E equipment industry, also for the strategic behavior of the firms.

Since many European governments pay subsidies on clean electricity via feed-in tariffs rather than subsidizing RES-E equipment directly, we have studied the performance of such policies compared to the first-best alternative. Second-best-optimal feed-in tariffs take account of the learning spill-overs in the RES-E equipment industry. If emission taxes do not (fully) internalize the externalities caused by using fossil-fuels, they also account for marginal pollution damage and the strategic output contraction caused by oligopolistic market structure in the fossil-fuel industry.

Although feed-in tariffs perform much worse than a first-best policy, our results suggest that in the presence of learning spill-overs in the RES-E equipment industry and oligopolistic competition in the fossil-fuel sector, feed-in tariffs for renewable electricity producers may be justified if first-best policies are ruled out and as long as emissions are not regulated by tradable emission allowances. Given the current situation where most European and other OECD economies' electricity markets are still dominated by a few large conventional utilities, our numerical results potentially call for a short-term *decrease* in feed-in tariff levels and a long-term *increase* in those levels as electricity markets are progressively liberalized. However, since our model considers environmental regulation of the conventional electricity sector through emission taxes, our results cannot be directly transferred to the current situation in the European Union, where CO₂ emitted by industrial sources is regulated through a cap-and-trade scheme of emission allowances. Under such a scheme, feed-in tariffs are not very useful as they have no further mitigating effects on emissions. In fact, they would induce a

lower allowance price and thus provide disincentives among the conventional electricity producers to further abate emissions (del Río Gonzalez, 2007; Sijm, 2005; Sorrel & Sijm, 2003). This problem could be solved by setting a more stringent emission cap accounting for the additional emission reductions achieved through the feed-in-tariff policy. Taxation of CO₂ emissions, by contrast, would render this adjustment of the emission cap superfluous.

In our model we have made several simplifying assumptions to keep the analysis tractable. In particular, we have assumed only one type of homogeneous RES-E equipment, while in reality several different types of RES-E equipment exist, for instance wind turbines, photovoltaic modules, and bio-gas power plants. Within each of these types further product differentiation exists. Some countries pay a unique feed-in tariff for "green" electricity independent of which type of RES-E equipment is used, whereas other countries, notably Germany, have a highly differentiated system of feed-in tariffs with a spread in feed-in rates of up to 500 percent. It must be left to further research to account for product differentiation of this kind and assess the resulting policy implications accordingly. Since the level of second-best optimal feed-in tariffs crucially depends on the degree of potential market power, it would be particularly interesting from an empirical viewpoint to test for market power in the RES-E equipment sector.

Chapter 2

An empirical model of carbon-constrained energy markets with an application to dynamic portfolio allocation

2.1 Introduction

In recent years energy markets in Europe and elsewhere have undergone important transformations. For instance, European governments and regulatory authorities have worked towards liberalizing the highly regulated national energy markets with the aim of creating a single and competitive European market. Moreover, the increasing use of standardized derivatives such as energy options and futures has improved overall market transparency and liquidity and has thus strengthened the link between the markets for different energy commodities such as electricity, natural gas, oil, and coal. In addition, a growing awareness concerning the negative environmental impacts of conventional, fossil-fuel based energy sources has led to the introduction of a wide array of environmental policy measures. One of the most prominent environmental policies is the European emissions trading scheme (EU-ETS). The EU-ETS has defined a cap on total industrial CO₂ emissions in the European Union and has set up a market where CO₂ emission rights, so called European emission allowances (EUAs) can be traded.

Turning CO₂ emissions from a free into a costly production factor alters the costs of fossil-fuel based energy generation and has important repercussions on production and consumption choices of all energy-related products. Therefore, optimal production and investment decision making in energy markets requires a clear understanding of the empirical interrelationships between energy prices, in particular prices for electricity, natural gas, and coal, and emission allowance prices.

In this chapter we contribute to the understanding of the interrelationships between electricity, natural gas, coal and emission allowances and to how these interrelations could be exploited for financial investment decisions. In particular we develop an empirical model representing the interrelationships between energy and allowance prices and returns and taking into account both the fundamental price drivers in the energy and emission markets and the volatility dynamics of the commodity returns. We propose a vector error correction model (VECM) approach with orthogonalized generalized autoregressive conditional heteroscedastic (GARCH) error processes. Within the latter empirical framework we can analyze both long-run relationships and short-run dynamics between CO₂ and energy prices in a very general fashion without imposing strict a-priori economic restrictions. In addition to the empirical analysis of the interrelationships of energy and CO₂ prices and returns, we consider an economic application where we use forecasts generated from the empirical model for dynamic portfolio allocation.

In theory a close relationship should exist between electricity, natural gas, coal, and emission allowances, where the latter three can be viewed as input factors for electric power production. Therefore, the prices for the three inputs should determine the power price in long-run market equilibrium. In the short run, however, interactions can take place among all endogenous variables. For instance, a constraint on CO₂ emissions can influence the type of generation plant to be employed, depending on the emission intensity of the fuel inputs. The reason is that in the short run, CO₂ abatement can be achieved through fuel switching from CO₂-intensive to less CO₂-intensive fuels, e.g. from lignite to hard coal or from hard coal to natural gas. Therefore, increasing prices of CO₂ emissions will lead to the employment of less emission-intensive power plants. In addition, changes in natural gas and coal prices can affect electricity prices both

through changing fuel input costs and through changes in the demand for emission allowances. The latter effect could occur when increasing costs of natural gas and coal lead to decreasing demand for these fuels. In this case, less CO₂ would be emitted and, since the supply of emission allowances is fixed by the European Commission, the price for emission allowances would decrease. Therefore, the decreasing allowance price could (partially) absorb the impact of increasing fuel costs on electricity prices. The price for electricity might also have feedback effects to the input markets. For instance, a sudden increase in the supply of renewable electricity can dampen the wholesale electricity price, crowd out conventional electricity production and thus reduce demand and prices of fossil fuels.

Finally, there are common exogenous factors that directly or indirectly affect prices on all four markets such as climatic conditions, economic growth, and regulatory issues. The latter is particularly important for the relatively young emission market, which is highly dependent on rules concerning among other issues the inflow of allowances from other trading schemes, banking and borrowing of allowances over several trading periods, and penalties for non-compliance.

Our study is in the spirit of Bunn & Fezzi (2007) and Fell (2010) who also use a VECM approach to analyze the relationship between CO₂, gas, and power prices in the United Kingdom and between CO₂, gas, coal and power prices and water reservoir levels in the Nordic region of Denmark, Finland, Norway, and Sweden, respectively. Moreover, there is a growing literature dealing with theoretical and empirical analysis of price determinants in emission allowance markets. In the context of the EU-ETS, the dynamic price behavior of emission allowances under uncertainty has been analyzed theoretically by Seifert *et al.* (2008), who take into account stylized facts of the European emission market. In addition, a handful of empirical papers have analyzed the price behavior of CO₂ allowances in the first trading phase of the EU-ETS. Among these, some authors have focused on short-term price changes and volatility dynamics of allowances relying on historical price information (Benz & Trück, 2009; Daskalakis *et al.*, 2009; Paolella & Taschini, 2008). Other authors have addressed the impact of CO₂ price fundamentals such as energy and weather variables on allowance prices (Alberola *et al.*, 2007; Hintermann, 2010; Mansanet-Bataller *et al.*, 2007; Rickels *et al.*, 2007). They find evidence that fossil-fuel prices, fuel-switching prices,

extreme and/or unanticipated variations in temperature and precipitation have influenced allowance prices in the first trading phase, although these relationships were not statistically significant throughout the entire period, probably due to the relative immaturity of the market.

In this chapter, we present several contributions to the empirical literature on energy and CO₂ prices. First, while previous studies have focused either on modeling the price determinants or the volatility dynamics in CO₂ markets via single equation models or on analyzing the interactions between energy and CO₂ prices via VAR/VECM models, we incorporate the three features in a VECM model with orthogonal GARCH (OGARCH) errors. Moreover, within our VECM-OGARCH framework we can analyze the impacts of unexpected shocks on energy and CO₂ prices by using an identification procedure that exploits the conditional heteroscedasticity of the statistical error terms without imposing a-priori restrictions on the contemporaneous coefficient matrix. Second, we test the economic performance of the empirical model by means of a portfolio allocation application. Unlike most of the above-mentioned empirical studies we analyze our model using futures prices instead of spot prices. The motivation for analyzing futures prices is that the physical nature of electricity, natural gas, and coal involves issues such as transportation and storage of the commodities, which would render a dynamic portfolio allocation, i.e. a frequent rebalancing of portfolio weights, more complicated and costly. Finally, we analyze the potential differences in the long run and short run interrelationships between energy and CO₂ prices with either baseload or peakload power prices.

The remainder of this chapter is organized as follows. The next section will explain the empirical model and the estimation procedure. In Section 2.3 we will describe the portfolio allocation problem and the forecasting procedure. Sections 2.4 and 2.5 will present the data and the empirical results of both the in-sample and the out-of-sample analysis. Finally, Section 2.6 will conclude.

2.2 The model

In this section we will derive the empirical model for power, emission allowances, natural gas, and coal returns. We will also discuss the model estimation procedure

and describe how to use the model for impulse-response analysis.

2.2.1 VECM with orthogonal GARCH errors

For the analysis of electricity, natural gas, coal, and CO₂ prices we choose a VECM approach providing a flexible framework to study the interactions between these variables both in the long-run equilibrium and in the short run. In the VECM we also incorporate exogenous factors, which are not part of the equilibrium relationship itself but are believed to affect the variables in the system particularly in the short-run, such as weather indices, oil prices, and economic growth rates. Finally, we model the innovations of the VECM by means of an orthogonal GARCH approach, which allows us to identify the contemporaneous interactions between the endogenous variables and to analyze the impact of shocks on the system.

In what follows let $p_{\bullet,t} = \ln(P_{\bullet,t})$ for $\bullet = e, a, g, c$ denote power, CO₂, natural gas, and coal prices in natural logarithms, respectively. We collect the prices in the vector $p_t = (p_{e,t}, p_{a,t}, p_{g,t}, p_{c,t})'$, which is decomposed in a deterministic and a stochastic part, i.e.

$$p_t = v_t + y_t, \quad (2.1)$$

where v_t is a deterministic trend and y_t follows a vector autoregressive process with exogenous variables of order q (VAR(q) henceforth):

$$y_t = A_1 y_{t-1} + \dots + A_q y_{t-q} + \lambda x_{t-1} + \varepsilon_t, \quad \varepsilon_t \sim N(0, \Sigma_t). \quad (2.2)$$

In our case, A_i with $i = 1, \dots, q$ is a 4×4 matrix of coefficients attached to the lags of the vector y_t and λ is a $4 \times L$ matrix of coefficients where L is the number of exogenous variables collected in the vector x_t . Moreover, $\varepsilon_t = (\varepsilon_{e,t}, \varepsilon_{a,t}, \varepsilon_{g,t}, \varepsilon_{c,t})'$ is a 4×1 vector of statistical innovations, which are multivariate normal with mean zero and time-varying covariance Σ_t . Inserting (2.2) in (2.1) and rearranging yields:

$$p_t = v_t^* + A_1 p_{t-1} + \dots + A_q p_{t-q} + \lambda x_{t-1} + \varepsilon_t, \quad (2.3)$$

where $v_t^* = f(v_t, A_1 v_{t-1}, \dots, A_q v_{t-q})$. Equation (2.3) implies that the vector of energy prices p_t can be modeled as a VAR(q) system, which expresses the price

vector as a function of a deterministic trend, past price values, a set of exogenous variables, and unsystematic shocks.

Following Granger (1981) and Engle & Granger (1987) the log prices in the vector p_t are cointegrated if they are integrated of order one (i.e. if they possess a unit root, denoted $I(1)$ for short) and if at least one linear combination of them exists that is integrated of order zero (i.e. the linear combination possesses no unit root, denoted $I(0)$ for short). The existence of cointegration relationships between non-stationary variables implies that these variables follow stable "long-run equilibrium" relationships. The cointegration concept can be applied in our context by means of a $VECM(q-1)$ which can be obtained by reparameterizing (2.1):

$$\Delta p_t = \Delta v_t + \Delta y_t, \quad (2.4)$$

where

$$\Delta y_t = \Pi y_{t-1} + \Gamma_1 \Delta y_{t-1} + \dots + \Gamma_{q-1} \Delta y_{t-q+1} + \lambda x_{t-1} + \varepsilon_t. \quad (2.5)$$

In this case, $\Delta p_t = p_t - p_{t-1}$ denotes the first difference of the log prices (or equivalently log returns) and $\Delta v_t = v_t - v_{t-1}$ and $\Delta y_t = y_t - y_{t-1}$ are the first differences of the deterministic and stochastic components, respectively. The coefficient matrices Π and Γ_i are given by $\Pi = -(I_4 - A_1 - \dots - A_q)$ and $\Gamma_i = -(A_{i+1} + \dots + A_q)$ for $i = 1, \dots, q-1$. The matrix Π can be written as $\Pi = \alpha\beta'$ where α and β are $(4 \times m)$ matrices of coefficients. The matrix α is usually referred to as the loading matrix and β as the cointegrating matrix. The parameter matrices α and β are not unique implying that identifying restrictions have to be imposed. Inserting (2.5) in (2.4) and rearranging yields:

$$\Delta p_t = \tilde{v}_t + \Pi p_{t-1} + \Gamma_1 \Delta p_{t-1} + \dots + \Gamma_{q-1} \Delta p_{t-q+1} + \lambda x_{t-1} + \varepsilon_t, \quad (2.6)$$

where $\tilde{v}_t = f(\Delta v_t, \Gamma_1 \Delta v_{t-1}, \dots, \Gamma_{q-1} \Delta v_{t-q}, \Pi v_{t-1})$.

To model the innovations ε_t we employ an orthogonal GARCH (OGARCH) specification in the spirit of Normandin & Phaneuf (2004). Among the variety of alternative multivariate specifications, we choose an OGARCH specification

for two main reasons. First, Normandin & Phaneuf (2004) argue that OGARCH processes can represent well the alternating periods of volatility and smoothness of the underlying time series. In addition, studies by van der Weide (2002) and Alexander (2002) show that OGARCH models work well in asset allocation settings. Second, the OGARCH specification describes the fundamental innovations of energy and CO₂ returns as a function of unobservable orthogonal and conditionally heteroscedastic shocks with loading matrix \mathbf{B} . According to the Arbitrage Pricing Theory we can thus interpret the unobservable shocks as risk factors. Therefore, the OGARCH specification implicitly prices the (short-term) risk in energy and CO₂ markets. Under this specification the statistical innovations are then given by:

$$\varepsilon_t = \mathbf{B}u_t, \text{ where } u_t \sim N(0, \Omega_t). \quad (2.7)$$

The vector $u_t = (u_{e,t}, u_{a,t}, u_{g,t}, u_{c,t})'$ contains the unobserved fundamental innovations and the matrix $\mathbf{D} = \mathbf{B}^{-1}$ describes the contemporaneous relations between the statistical innovations ε_t . It is assumed that the fundamental innovations in u_t are uncorrelated and that each $u_{\bullet,t}$ for $\bullet = e, a, g, c$ has an unconditional variance equal to 1, i.e. $E[u_t u_t'] = \Omega = I_4$, where I_4 is an identity matrix of size 4. The conditional covariance Σ_t is then given by

$$\Sigma_t = E[\varepsilon_t \varepsilon_t' | F_{t-1}] = \mathbf{B} \Omega_t \mathbf{B}', \quad (2.8)$$

where $E[\bullet]$ is the expectations operator, F_t denotes the information available at time t and Ω_t follows a diagonal GARCH structure of the form:

$$\Omega_t = (I_4 - \mathbf{C}_1 - \mathbf{C}_2) + \mathbf{C}_1 \odot (u_{t-1} u_{t-1}') + \mathbf{C}_2 \odot \Omega_{t-1}, \quad (2.9)$$

where $\Omega_t = \text{diag}(\omega_{e,t}, \omega_{a,t}, \omega_{g,t}, \omega_{c,t})$, \odot denotes element-by-element multiplication and \mathbf{C}_1 and \mathbf{C}_2 are diagonal matrices of coefficients.

If \mathbf{C}_1 and \mathbf{C}_2 are zero matrices, i.e. Ω_t is time-invariant, the fundamental innovations become homoscedastic. In that case $\Sigma = \mathbf{B}\mathbf{B}'$ but \mathbf{B} is not uniquely identifiable. The traditional VAR/VECM model typically imposes conditionally homoscedastic fundamental disturbances and a popular approach to identify the

contemporaneous interrelationships between the shocks in u_t consists in performing a Cholesky decomposition of the covariance matrix Σ such that $\Sigma = \mathbf{P}\mathbf{P}'$ where \mathbf{P} is a lower triangular matrix. Alternatively, the so-called structural VAR/VECM (SVAR/SVECM) models with homoscedastic innovations require (economically motivated) restrictions for the parameters contained in $\mathbf{D} = \mathbf{B}^{-1}$ in order to identify \mathbf{B} .¹ By contrast, with conditionally heteroscedastic fundamental disturbances $u_{\bullet,t}$, the matrix \mathbf{B} can be uniquely identified.²

In our framework, conditional correlations between the statistical innovations can be obtained as

$$\rho_t = \text{diag}(\Sigma_t)^{-1/2} \cdot \Sigma_t \cdot \text{diag}(\Sigma_t)^{-1/2}, \quad (2.10)$$

allowing us to analyze the short-run co-movements between the innovations ε_t .

For illustration purposes, consider a VECM with one cointegration relationship $m = 1$ and lags $q = 2$. The term Πp_{t-1} representing the long-run relationship in (2.6) is then written as

$$\Pi p_{t-1} = \underbrace{\begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \end{pmatrix}}_{\alpha} \underbrace{\begin{pmatrix} \beta_1 & \beta_2 & \beta_3 & \beta_4 \end{pmatrix}}_{\beta} \begin{pmatrix} p_{e,t-1} \\ p_{a,t-1} \\ p_{g,t-1} \\ p_{c,t-1} \end{pmatrix}. \quad (2.11)$$

To identify the long-run relationship between the prices, we can normalize β_1 in the vector β to unity so that $\beta_2^* = \beta_2/\beta_1$, $\beta_3^* = \beta_3/\beta_1$, $\beta_4^* = \beta_4/\beta_1$. The term Πp_{t-1} then becomes

$$\Pi p_{t-1} = \alpha z_{t-1} = \begin{pmatrix} \alpha_1 z_{t-1} \\ \alpha_2 z_{t-1} \\ \alpha_3 z_{t-1} \\ \alpha_4 z_{t-1} \end{pmatrix}, \quad (2.12)$$

¹In the SVAR model, the Maximum Likelihood methodology is required to estimate $\hat{\mathbf{D}} = \hat{\mathbf{B}}^{-1}$, while in the traditional VAR model the Cholesky decomposition can be performed with an estimate of $\hat{\Sigma}$ obtained from the OLS residuals.

²For details, see Normandin & Phaneuf (2004).

where

$$p_{e,t} = \tilde{\beta}_2 p_{a,t} + \tilde{\beta}_3 p_{g,t} + \tilde{\beta}_4 p_{c,t} + z_t \quad (2.13)$$

describes the long-run equilibrium relationship between electricity, emission allowance, natural gas, and coal prices, z_t is the "long-run" error between the prices, and the parameters $\tilde{\beta}_i = -\beta_i^*$ for $i = 2, 3, 4$ can be interpreted as the elasticities of EUA, gas, and coal prices with respect to the electricity price. Note that the VECM prices the "long-term" risk in energy and CO₂ markets through the error correction term z_t (Bansal & Kiku, 2011). The system of dynamic equations in (2.6) is then given by:

$$\begin{aligned} \Delta p_{e,t} &= \tilde{v}_{e,t} + \alpha_1 z_{t-1} + \gamma_{11} \Delta p_{e,t-1} + \gamma_{12} \Delta p_{a,t-1} + \gamma_{13} \Delta p_{g,t-1} \\ &+ \gamma_{14} \Delta p_{c,t-1} + \lambda'_1 x_{t-1} + \varepsilon_{e,t}, \end{aligned} \quad (2.14)$$

$$\begin{aligned} \Delta p_{a,t} &= \tilde{v}_{a,t} + \alpha_2 z_{t-1} + \gamma_{21} \Delta p_{e,t-1} + \gamma_{22} \Delta p_{a,t-1} + \gamma_{23} \Delta p_{g,t-1} \\ &+ \gamma_{24} \Delta p_{c,t-1} + \lambda'_2 x_{t-1} + \varepsilon_{a,t}, \end{aligned} \quad (2.15)$$

$$\begin{aligned} \Delta p_{g,t} &= \tilde{v}_{g,t} + \alpha_3 z_{t-1} + \gamma_{31} \Delta p_{e,t-1} + \gamma_{32} \Delta p_{a,t-1} + \gamma_{33} \Delta p_{g,t-1} \\ &+ \gamma_{34} \Delta p_{c,t-1} + \lambda'_3 x_{t-1} + \varepsilon_{g,t}, \end{aligned} \quad (2.16)$$

$$\begin{aligned} \Delta p_{c,t} &= \tilde{v}_{c,t} + \alpha_4 z_{t-1} + \gamma_{41} \Delta p_{e,t-1} + \gamma_{42} \Delta p_{a,t-1} + \gamma_{43} \Delta p_{g,t-1} \\ &+ \gamma_{44} \Delta p_{c,t-1} + \lambda'_4 x_{t-1} + \varepsilon_{c,t}. \end{aligned} \quad (2.17)$$

The statistical innovations $\varepsilon_{\bullet,t}$ are given by:

$$\varepsilon_{e,t} = b_{11} u_{e,t} + b_{12} u_{a,t} + b_{13} u_{g,t} + b_{14} u_{c,t}, \quad (2.18)$$

$$\varepsilon_{a,t} = b_{21} u_{e,t} + b_{22} u_{a,t} + b_{23} u_{g,t} + b_{24} u_{c,t}, \quad (2.19)$$

$$\varepsilon_{g,t} = b_{31} u_{e,t} + b_{32} u_{a,t} + b_{33} u_{g,t} + b_{34} u_{c,t}, \quad (2.20)$$

$$\varepsilon_{c,t} = b_{41} u_{e,t} + b_{42} u_{a,t} + b_{43} u_{g,t} + b_{44} u_{c,t}. \quad (2.21)$$

Finally, we assume $u_{\bullet,t} \sim N(0, \omega_{\bullet,t})$ for $\bullet = e, a, g, c$, where the time-varying

variances $\omega_{\bullet,t}$ follow GARCH(1,1) processes, i.e.

$$\omega_{e,t} = (1 - c_{11} - c_{12}) + c_{11}u_{e,t-1}^2 + c_{12}\omega_{e,t-1}, \quad (2.22)$$

$$\omega_{a,t} = (1 - c_{21} - c_{22}) + c_{21}u_{a,t-1}^2 + c_{22}\omega_{a,t-1}, \quad (2.23)$$

$$\omega_{g,t} = (1 - c_{31} - c_{32}) + c_{31}u_{g,t-1}^2 + c_{32}\omega_{g,t-1}, \quad (2.24)$$

$$\omega_{c,t} = (1 - c_{41} - c_{42}) + c_{41}u_{c,t-1}^2 + c_{42}\omega_{c,t-1}. \quad (2.25)$$

It will be useful for the following sections on portfolio allocation to express the full VECM model in (2.6) compactly in a conditional model of log returns:

$$r_t = \mu_t + \varepsilon_t, \quad (2.26)$$

$$\text{where } \mu_t = \tilde{v}_t + \Pi p_{t-1} + \sum_{j=1}^{q-1} \Gamma_j r_{t-j} + \lambda x_{t-1} \quad (2.27)$$

$$\text{and } \varepsilon_t \sim N(0, \Sigma_t).$$

In (2.26) and (2.27) $r_t \equiv \Delta p_t$ defines the vector of returns, $\mu_t \equiv E[r_t|F_{t-1}]$ is the conditional mean, and $\Sigma_t \equiv E[(r_t - \mu_t)(r_t - \mu_t)'|F_{t-1}]$ is the conditional covariance.

2.2.2 Impulse responses

The contemporaneous and dynamic interactions between the returns of electricity, natural gas, coal, and emission allowances can be analyzed by computing the impulse-response functions of a one-time shock on the fundamental innovations $u_t = (u_{e,t}, u_{a,t}, u_{g,t}, u_{c,t})'$ in (2.7), where the initial impact of shocks on the endogenous variables is determined by the contemporaneous coefficients in the matrix \mathbf{B} and the effect of the shocks at larger horizons is governed by the parameters Γ_i in the VECM in (2.6).

For illustration purposes, consider the case $q = 2$ and $\tilde{v}_t = v$. Defining $r_{t-1} = Lr_t$ where L is the lag operator, we can rewrite the model (2.26) as follows:

$$r_t = (I_4 - \Gamma_1 L)^{-1}(\tilde{\mu}_t + \varepsilon_t), \quad (2.28)$$

where $\tilde{\mu}_t = v + \Pi p_{t-1} + \lambda x_{t-1}$ and ε_t is defined by equation (2.7). Solving (2.28) yields

$$\begin{aligned} r_t &= \tilde{\mu}_t + \Gamma_1 \tilde{\mu}_{t-1} + \Gamma_1^2 \tilde{\mu}_{t-2} + \dots + \varepsilon_t + \Gamma_1 \varepsilon_{t-1} + \Gamma_1^2 \varepsilon_{t-2} + \dots, \\ &= \tilde{\mu}_t + \Gamma_1 \tilde{\mu}_{t-1} + \Gamma_1^2 \tilde{\mu}_{t-2} + \dots + \mathbf{B}u_t + \Gamma_1 \mathbf{B}u_{t-1} + \Gamma_1^2 \mathbf{B}u_{t-2} + \dots \end{aligned} \quad (2.29)$$

The response of the endogenous variables in r_t to a shock on one of the fundamental innovations at an arbitrary horizon h can be obtained by partially differentiating (2.29) with respect to $u_{\bullet,t-h}$ for $\bullet = e, a, g, c$. For instance, the initial response of electricity returns to a shock on the structural innovations of emission allowances is determined by $\partial r_{e,t} / \partial u_{a,t} |_{h=0} = b_{12}$ (see equation (2.18)). A similar logic applies for higher horizons $h > 1$ where the dynamics enter via Γ_1^h .

2.2.3 Estimation procedure

We estimate model (2.26) in three main steps. The first step consists of estimating the long-run coefficients β by means of the Johansen reduced rank procedure (Johansen, 1995). The second step consists of estimating the short-run coefficients v, α, Γ_i , and λ by means of Ordinary Least Squares (OLS). For the computation of the standard errors of the VECM parameters, we use the heteroscedasticity-consistent covariance matrix estimator proposed by White (1980).³

In the third step, following Normandin & Phaneuf (2004), we use the OLS estimates of the statistical innovations $\hat{\varepsilon}_t$ to estimate the contemporaneous and GARCH parameters \mathbf{B} , \mathbf{C}_1 , and \mathbf{C}_2 , respectively, by means of maximum likelihood. The log-likelihood of the sample assuming that the statistical innovations are conditionally Gaussian is given by

$$L(\Theta|\varepsilon) = -\frac{4T}{2} \log(2\pi) - \frac{1}{2} \sum_{t=1}^T \log(|\Sigma_t|) - \frac{1}{2} \sum_{t=1}^T \hat{\varepsilon}_t' \Sigma_t^{-1} \hat{\varepsilon}_t, \quad (2.30)$$

where $\varepsilon = (\hat{\varepsilon}_1, \dots, \hat{\varepsilon}_T)'$ are the observations and Θ is a vector containing the

³We also experimented with Generalized Least Squares estimation but the results were qualitatively similar.

elements of \mathbf{B} , \mathbf{C}_1 , and \mathbf{C}_2 . The log-likelihood is maximized over the parameter space Θ using the Berndt-Hall-Hall-Hausman (BHHH) optimization algorithm.

2.3 Portfolio allocation and dynamic trading strategies

In this section we will present an application of our empirical model to a portfolio allocation problem of an investor holding power, natural gas, coal, and emission allowance futures in his portfolio. Such a portfolio analysis could be relevant for investors following hedging or speculation motives that will be described in the next section. We will then present the derivation of optimal time-varying portfolio weights for different investment objectives and describe the methodology for forecasting the conditional mean and covariance from our empirical model. Finally, we will discuss measures to test the performance of dynamic trading strategies based on the different investment objectives.

2.3.1 Trading commodity futures

A futures contract is a derivative contract whose value depends on the value of an underlying asset such as an equity or commodity. It consists of an agreement between two entities to buy or sell an asset at a certain maturity date at today's price of the futures contract. More precisely, the buyer of a futures contract buys the underlying asset at the current price (long position) and sells it at a future date at an unknown price. On the other hand, the seller of a futures contract sells the underlying asset at the current price (short position) and buys it back at a future date at an unknown price. Thus, the buyer (seller) of a futures contract benefits from increasing (decreasing) prices of the underlying asset in the future.

A futures contract generally contains standardized features such as the quantity and quality of the underlying asset, the date of delivery, the units of price quotation, the minimum price changes, and the form of settlement. The main difference between commodity and financial futures concerns the settlement of the contracts, which in the case of commodity futures usually involves the physical delivery of the underlying commodity. Physical delivery of commodity futures

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raises important issues that do not arise in the case of financial futures where the physical attribute is missing, such as storage facilities and costs, capacity constraints, transport costs, and the quality of the asset. However, some commodity futures may also be cash-settled according to the spot price of the underlying commodity at the respective settlement date.

The final settlement price of a futures contract is determined at the end of the last trading day and delivery of the underlying commodity or cash-settlement is executed at this price. A futures contract can also be offset prior to its maturity date by entering into an equal opposite transaction. Participation in futures trading serves three main objectives: hedging, speculation, and arbitrage that will be briefly explained in the following.

- **Hedging:** A market participant who wishes to reduce the risk associated with the price development of an asset can use futures contracts to hedge against this risk. For example, a producer of coal-generated electricity who wants to hedge against the risk of coal price increases in the future may conclude a hedging transaction by buying a corresponding amount of coal futures at the current market price (long hedge). If the coal price effectively increases in the future, he can offset the additional input costs through the revenues from selling the coal futures. On the other hand, if the coal price decreases in the future he can offset the loss on the futures position through lower production input costs. Therefore, the objective of hedging is not to make profits but to fix a price for the future.
- **Speculation:** A market participant who wants to make profits by speculating on future price movements of a commodity without having to handle the issues of transportation and storage of the commodity can open a long (short) position in a corresponding futures contract depending on whether he speculates on the commodity price to increase (decrease) in the future.
- **Arbitrage:** A market participant who takes advantage of the divergence between prices of the same product across different markets can obtain arbitrage profits by taking offsetting positions in the two markets. Similarly, arbitrage opportunities arise when the price of a futures contract deviates

2.3 Portfolio allocation and dynamic trading strategies

from its fair value, which, according to the cost-of-carry model, is given by the discounted value of the spot price and the present value of all storage costs. Thus, arbitrage ensures that the futures price converges to the spot price of the underlying commodity upon expiry of the futures contract.

2.3.2 The portfolio allocation problem

In the following we will analyze the optimal dynamic portfolio choice of a risk averse investor in a mean-variance framework. For this purpose, let τ denote an arbitrary point in time such that $\tau \in (1, 2, \dots, T)$. For simplicity of exposition, we consider an investor with investment horizon h at $\tau + h|_{h=1}$. The investors' preferences are defined over the conditional mean and covariance of future returns, given by $\mu_{\tau+1|\tau} \equiv E[r_{\tau+1}|F_\tau]$, and $\Sigma_{\tau+1|\tau} \equiv E[(r_{\tau+1} - \mu_{\tau+1|\tau})(r_{\tau+1} - \mu_{\tau+1|\tau})'|F_\tau]$, respectively, where F_τ denotes the current information available at time τ . We further let $\mu_{p,\tau+1}$, and $\sigma_{p,\tau+1}^2$ denote the conditional mean and variance of the portfolio returns $r_{p,\tau+1}$ at time $\tau + 1$. Following Han (2006), we analyze the portfolio allocation problem under three different mean-variance objectives.

Strategy 1: The investor seeks to maximize his expected mean-variance utility function at time τ given by

$$\begin{aligned} \max \{ & E[u(W_{\tau+1})] = \mu_{p,\tau+1} - \frac{\gamma}{2}\sigma_{p,\tau+1}^2 \}, & (2.31) \\ \text{with } & \mu_{p,\tau+1} = w'_{1,\tau}\mu_{\tau+1|\tau} + (1 - w'_{1,\tau}\mathbf{1})i_f, \\ \text{and } & \sigma_{p,\tau+1}^2 = w'_{1,\tau}\Sigma_{\tau+1|\tau}w_{1,\tau}, \end{aligned}$$

where $W_{\tau+1}$ denotes terminal wealth, $w_{1,\tau}$ is a vector of portfolio weights, γ is the coefficient of absolute risk aversion, and i_f is the return on the risk-free asset. The solution to the maximization problem yields the optimal portfolio weights:

$$w_{1,\tau} = \frac{1}{\gamma}\Sigma_{\tau+1|\tau}^{-1}(\mu_{\tau+1|\tau} - \mathbf{1}i_f). \quad (2.32)$$

Strategy 2: The investor wishes to minimize volatility by minimizing the conditional variance for a given level of conditional expected return. The investor

2.3 Portfolio allocation and dynamic trading strategies

then solves

$$\begin{aligned} \min \{ & \sigma_{p,\tau+1}^2 = w'_{2,\tau} \Sigma_{\tau+1|\tau} w_{2,\tau} \} \\ \text{s.t. } & w'_{2,\tau} \mu_{\tau+1|\tau} + (1 - w'_{2,\tau} \mathbf{1}) i_f = \mu_p^*, \end{aligned} \quad (2.33)$$

where $w_{2,\tau}$ and μ_p^* are the vector of optimal portfolio weights and the target expected return, respectively. The resulting portfolio weights are

$$\begin{aligned} w_{2,\tau} &= \Sigma_{\tau+1|\tau}^{-1} (\mu_{\tau+1|\tau} - \mathbf{1} i_f) \frac{\mu_p^* - i_f}{\kappa_\tau} \\ \text{with } \kappa_\tau &= (\mu_{\tau+1|\tau} - \mathbf{1} i_f)' \Sigma_{\tau+1|\tau}^{-1} (\mu_{\tau+1|\tau} - \mathbf{1} i_f). \end{aligned} \quad (2.34)$$

Strategy 3: The investor aims at maximizing the conditional expected return for a given level of conditional volatility σ_p^* . The objective function then becomes

$$\begin{aligned} \max \{ & \mu_{p,\tau+1} = w'_{3,\tau} \mu_{\tau+1|\tau} + (1 - w'_{3,\tau} \mathbf{1}) i_f \} \\ \text{s.t. } & w'_{3,\tau} \mu_{\tau+1|\tau} + (1 - w'_{3,\tau} \mathbf{1}) i_f = (\sigma_p^*)^2, \end{aligned} \quad (2.35)$$

where the vector of optimal portfolio weights $w_{3,\tau}$ is given by

$$w_{3,\tau} = \Sigma_{\tau+1|\tau}^{-1} (\mu_{\tau+1|\tau} - \mathbf{1} i_f) \sqrt{\frac{(\sigma_p^*)^2}{\kappa_\tau}}. \quad (2.36)$$

2.3.3 Forecasting methodology

The trading strategies discussed in the previous section will be analyzed at various rebalancing horizons h . Let $\widehat{\Pi}, \widehat{\Gamma}_i, \widehat{\lambda}, \widehat{B}, \widehat{C}_1, \widehat{C}_2$ denote estimated parameters of the VECM-OGARCH model. Following Lütkepohl (2007), forecasts of the conditional mean for horizons $h = 1, 2, \dots, H$ at time τ are computed recursively as follows:

$$\widehat{\mu}_{\tau+h|\tau} = \widehat{v}_{\tau+h} + \widehat{\Pi} z_{\tau+h-1|\tau} + \widehat{\Gamma}_1 r_{\tau+h-1|\tau} + \dots + \widehat{\Gamma}_{q-1} r_{\tau+h-q|\tau} + \widehat{\lambda} x_{\tau+h-1|\tau}. \quad (2.37)$$

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Given $\widehat{\Omega}_{\tau+1}$ obtained from (2.9), forecasts of the conditional variance for horizons $h = 2, \dots, H$ at time τ are computed recursively as follows:

$$\widehat{\Sigma}_{\tau+h|\tau} = \widehat{\mathbf{B}}\widehat{\Omega}_{\tau+h|\tau}\widehat{\mathbf{B}}', \quad (2.38)$$

$$\widehat{\Omega}_{\tau+h|\tau} = I_4 + (\widehat{\mathbf{C}}_1 + \widehat{\mathbf{C}}_2)^{h-1}(\widehat{\Omega}_{\tau+1} - I_4). \quad (2.39)$$

2.3.4 Performance measures

To evaluate the risk and return performance of the dynamic trading strategies generated from the different investment objectives we follow Han (2006) in computing three measures for risk-adjusted returns, the ex-ante and ex-post Sharpe ratios (Sharpe, 1966), and the Modigliani risk-adjusted performance measure (Modigliani & Modigliani, 1997). The Sharpe ratios are calculated as follows:

$$\mathcal{SR} = \frac{(\mu_p - i_f)}{\sigma_p}, \quad (2.40)$$

where μ_p and σ_p are the ex-ante or ex-post mean and standard deviation of the portfolio returns and i_f is the risk-free interest rate. According to (2.40) the Sharpe ratio measures the excess return of an investment per unit of risk. Therefore, a higher Sharpe ratio implies a higher compensation for the risk incurred compared to the risk-free rate. However, the Sharpe ratio has a major weakness as it is difficult to interpret the difference between the Sharpe ratios of different trading strategies, for instance how much better is a trading strategy with $\mathcal{SR} = 0.3$ compared to a strategy with $\mathcal{SR} = 0.1$.

Alternatively, the Modigliani risk-adjusted performance measure ($\mathcal{M}2$) computes the risk-adjusted return of a portfolio relative to the (market) benchmark. It can be derived from the Sharpe ratio and has the advantage of yielding the investment's performance relative to the benchmark in percentage terms. This makes the Modigliani measure easier to interpret than the Sharpe ratio. The $\mathcal{M}2$ measure is given by

$$\mathcal{M}2 = \frac{\sigma_b}{\sigma_p}(\mu_p - i_f) - (\mu_b - i_f) = \sigma_b(\mathcal{SR}_p - \mathcal{SR}_b), \quad (2.41)$$

where μ_b , σ_b , and \mathcal{SR}_b are the mean, the standard deviation, and the Sharpe ratio of the benchmark portfolio, respectively. Therefore, the $\mathcal{M}2$ measure expresses the return an investment with a given risk and return would have achieved if it had the same risk as the benchmark portfolio. A higher value of $\mathcal{M}2$ thus implies a higher risk-adjusted return of an investment or trading strategy compared to the benchmark (Simons, 1998).

2.4 Data

2.4.1 Endogenous variables

We use prices of future contracts of power, natural gas, coal, and EU allowances (in natural logarithmic scale) as endogenous variables in the VECM. All contracts are traded on the European Energy Exchange (EEX), one of the major energy exchanges in continental Europe. Our analysis focuses on the second trading phase of the EU-ETS from 2008 – 2012 since according to Rickels *et al.* (2007) and Hintermann (2010), common stochastic trends in the EUA and fossil-fuel prices were absent in the first trading phase, most probably due to the immaturity of the emission market. In particular, our sample period ranges from July 2007, when natural gas trading was launched at the EEX, until November 2009.

We use futures contracts with similar maturities in order to avoid price differences arising from different maturity dates. In particular, the power, natural gas, and coal futures contracts are year futures with delivery in January 2010. Since EUA futures contracts already reach maturity in December, we use the futures contract with the closest possible maturity to the other futures, i.e. the December 2009 futures. All prices are converted to €/tCO₂.⁴ An alternative would have been to measure all prices in €/MWh, but to our knowledge there is no standard way of converting emission allowances denoted in tCO₂ to MWh.

⁴The coal price is converted from US-Dollar (\$) to Euro (€) with the exchange rate published by the European Central Bank. To convert the prices from MWh to tCO₂ we use the following emission factors: 0.2016 tCO₂/MWh for natural gas, 0.3384 tCO₂/MWh for bituminous coal, and 0.572 tCO₂/MWh for the German power mix in 2008 (including fossil-fuel, nuclear, and renewable energy). The emission factors for gas, coal, and power are provided by Umweltbundesamt (2010) and Umweltbundesamt (2011), respectively.

Figure 2.1 shows plots of the prices of power (baseload and peakload), emission allowance, natural gas, and coal futures. All price plots display a sharp increase of the commodity prices in 2007 and 2008, mainly driven by increasing demand for fossil-fuels such as crude oil and coal from developing countries such as China and India. This development was followed by a sudden price drop starting in the second half of 2008, when the financial crisis triggered on the U.S. subprime credit market began to impact on the global economy. Similarly, the low price levels in 2009 were characterized by declining demand for energy due to the economic downturn. In the case of emission allowances, 2007 was the last year of the first trading period, which had been characterized by a large excess supply of emission allowances, causing EUA spot prices to drop to zero by the end of the year. Therefore, the high price level of EUA futures in 2007 shows that the market was already expecting a tighter allowance allocation in the second trading period.

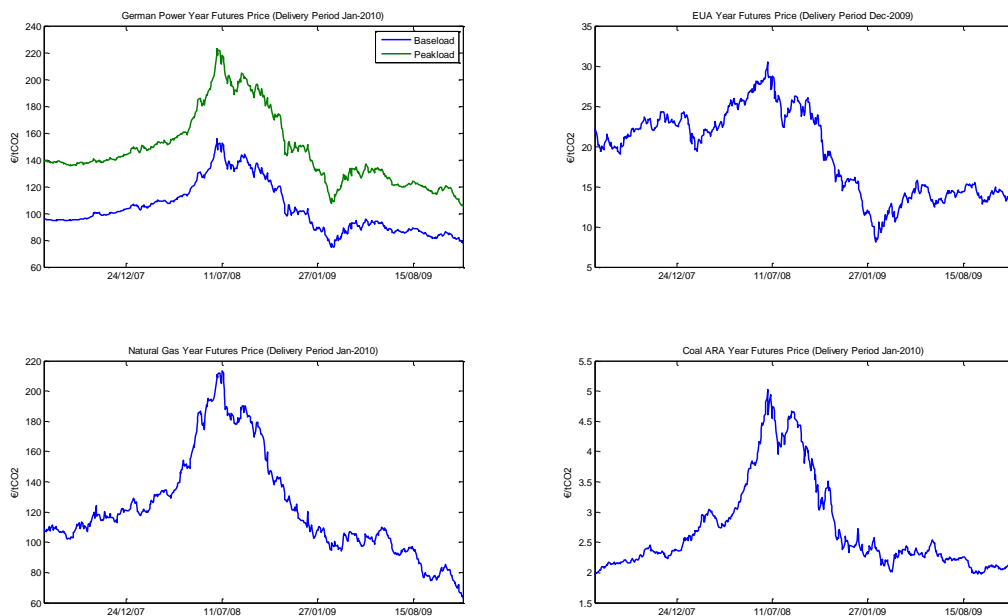


Figure 2.1: Prices of power, natural gas, coal, and EUA futures

Table 2.1 summarizes the main characteristics of the EEX futures contracts. Cascading of futures means that before the beginning of the delivery period every open position in year futures is replaced with equivalent positions in month

futures for the delivery months from January until March and quarter futures for the second through to the fourth delivery quarter, where the delivery periods taken together correspond to the delivery year. Similarly, open positions in quarter futures are cascaded into equivalent positions in month futures before the commencement of the delivery period. In other words, before the beginning of the delivery period a trader holding an open position in a natural gas year future with delivery in January 2010 will receive three natural gas month future contracts for the months from January to March 2010 and three natural gas quarter future contracts for the second, third, and fourth quarter of the year 2010. Ultimately, the EEX natural gas futures are settled physically, i.e. the buyer (seller) of a natural gas month future is obliged to buy (deliver) the agreed quantity of gas during every delivery day of the delivery month at the final settlement price.⁵ Similarly, the German power month future is settled physically through the delivery of power into the area of the German transmission operator Amprion. By contrast, the EEX coal month future is settled financially, where the final settlement price is established on the basis of the underlying coal index from the Argus/McCloskey Coal Price Index Report. Thus, EEX coal futures can be traded for hedging or speculation purposes, but not with the aim of obtaining physical delivery of coal. Finally, the EUA future is settled through delivery on the first trading day in December of the corresponding delivery year.

⁵Natural gas contracts for two different market areas can be traded on the EEX (Gaspool and NetConnect Germany), which together correspond to 95% of the natural gas volume sold in Germany.

Table 2.1: Characteristics of EEX year futures contracts

Contract	Underlying	Delivery Period	Fulfilment
German Power Future	Physical delivery of power	Jan 2010	Cascading/ Physical settlement
Natural Gas Future (NCG)	Physical delivery of natural gas	Jan 2010	Cascading/ Physical settlement
Coal ARA Future	Argus/McCloskey API 2 coal price index	Jan 2010	Cascading/ Cash settlement
EUA Future	EU allowances for the 2nd commitment period	Dec 2009	Delivery

2.4.2 Exogenous variables

As exogenous variables in the VECM we use Brent crude oil spot returns (in natural logarithm, denoted in $\text{€}/\text{tCO}_2$), earnings growth in the utility sector, and several weather-related indices.⁶ Although oil is not a major primary energy input used in European utilities, its price level and volatility is generally considered an important determinant of other energy-related prices and volatilities. We therefore consider oil returns as an exogenous variable. In addition, we calculate earnings growth of the DAX Utilities Xetra Index, which we interpret as a proxy for economic growth in the utility sector.⁷

In addition, energy and CO_2 prices may be affected by climatic conditions. For instance, temperatures above or below their average level lead to above-average energy demand (for heating and cooling), inducing an upward pressure on energy and CO_2 prices. Moreover, above-average precipitation reduces demand for conventional energy sources due to higher production by hydroelectric utilities and will thus have a mitigating impact on energy and CO_2 prices. We also compute squared terms of the temperature and precipitation series. The reason is that there may be nonlinear relationships between climate and energy demand. For

⁶For the sake of brevity, here we only describe the weather indices used in the main model specification. Appendix B.1 provides the description of the weather indices used in the alternative specifications.

⁷The DAX Utilities Index is a sectorial index including electricity and water utilities, oil and gas distribution utilities, and multi-utilities.

instance, when the reservoirs of hydroelectric utilities approach their capacity limits, additional precipitation is expected to have a smaller effect on hydroelectric production than when reservoirs are empty. By contrast, temperature may have an increasing marginal effect on energy demand, because energy demand increases for both very low and very high levels of outside temperature. According to Hintermann (2010), traders in the energy markets are likely to take into account not only the weather on a given day, but also past and forecasted weather. We therefore follow his approach in calculating 5-day moving averages of the daily weather deviations from their historical mean.

We use daily climate data from more than 50 weather stations in Europe (Germany, France, Spain, and Italy). We aggregate the temperature data by multiplying each series with its respective regional population weight since, presumably, temperatures in more populated regions might have a larger impact on energy prices than temperatures in less populated regions. Similarly, we weigh the precipitation series according to hydroelectric capacity in each country.⁸

Finally, we construct seasonal dummy variables that are vectors containing zeros and ones as entries. For instance, entries in the summer dummy receive the value 1 when the day falls into the summer season (April-October) and 0 otherwise. The weather data is obtained from the European Climate Assessment and Dataset (<http://eca.knmi.nl>). The data on Brent crude oil spot prices and the DAX Utilities index (price index and price-earnings ratio) are obtained from Datastream. Table 2.2 summarizes the exogenous variables used in the main model specification.

Table 2.2: Exogenous variables

Index	Description
OIL_t	Brent spot returns
EAR_t	Earnings growth rate of the DAX Utilities Xetra Index
MAT_t, MAT_t^2	5-day moving average of temperature deviation and squared term
MAP_t, MAP_t^2	5-day moving average of precipitation deviation and squared term
DS_t, DW_t	Dummy for the summer (S) and winter (W) season

⁸Appendix B.1 provides a detailed description of the construction of the weather indices.

2.4.3 Descriptive statistics

The descriptive statistics of the log returns of power (baseload and peakload), emission allowances, natural gas, and coal futures are summarized in Table 2.3. Figure 2.2 illustrates the distribution of log returns. Figures 2.3 and 2.4 show plots of the log returns, the squared log returns and the corresponding autocorrelation functions. Together with Table 2.3 the plots indicate that the future price series have typical asset price characteristics such as non-stationarity in levels (see Figure 2.1), non-normal distribution of returns, excess kurtosis, and volatility clustering. Although the log returns are mostly uncorrelated, the squared log returns exhibit some autocorrelation, which appears to die out slowly at higher lags. To confirm the non-stationarity of the log price series we perform several unit-root tests. The unit-root test results are provided in Appendix B.2.

In addition, Table 2.3 shows that the average returns of power, natural gas, and emission allowances were negative for the analyzed sample period. This suggests that an investor would have had a negative return had he or she bought and held a position in one of these commodities. To what extent an investor would have improved such an outcome within a portfolio of these assets will be treated in Section 2.5.2.1.

Table 2.3: Descriptive statistics of log returns

Log returns	Mean	Std. dev.	Kurtosis	Skewness
Power baseload	-0.0294	1.4385	7.4985	-0.2079
Power peakload	-0.0550	1.7818	6.6904	-0.1176
EUA	-0.0145	0.4307	4.3270	-0.4375
Natural Gas	-0.0775	2.2193	6.6619	0.2716
Coal	0.0001	0.0599	9.4682	-0.8517

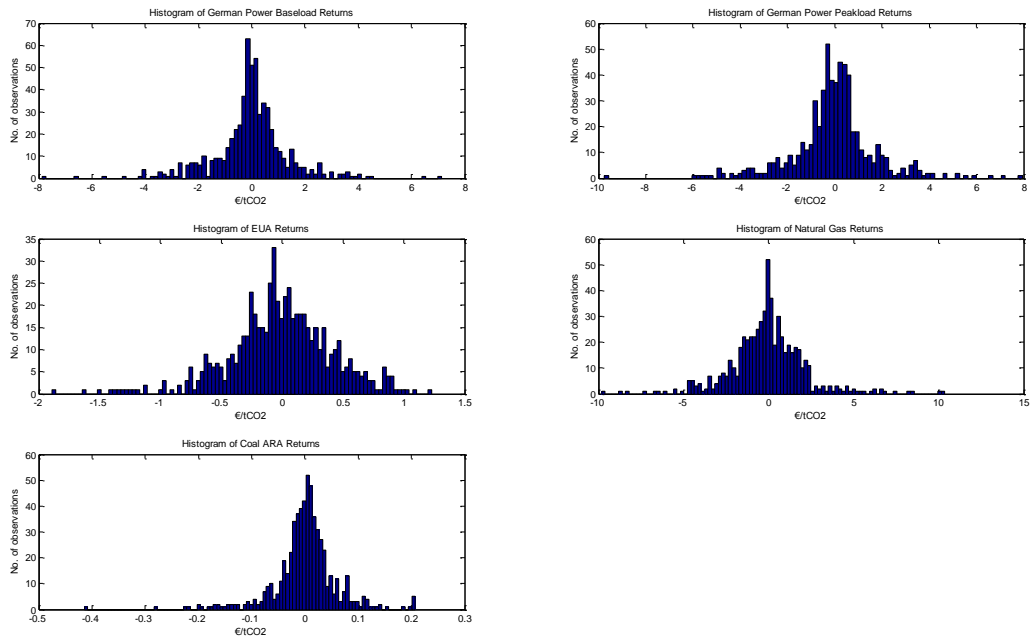


Figure 2.2: Histograms of log returns of power, natural gas, coal, and EUA futures

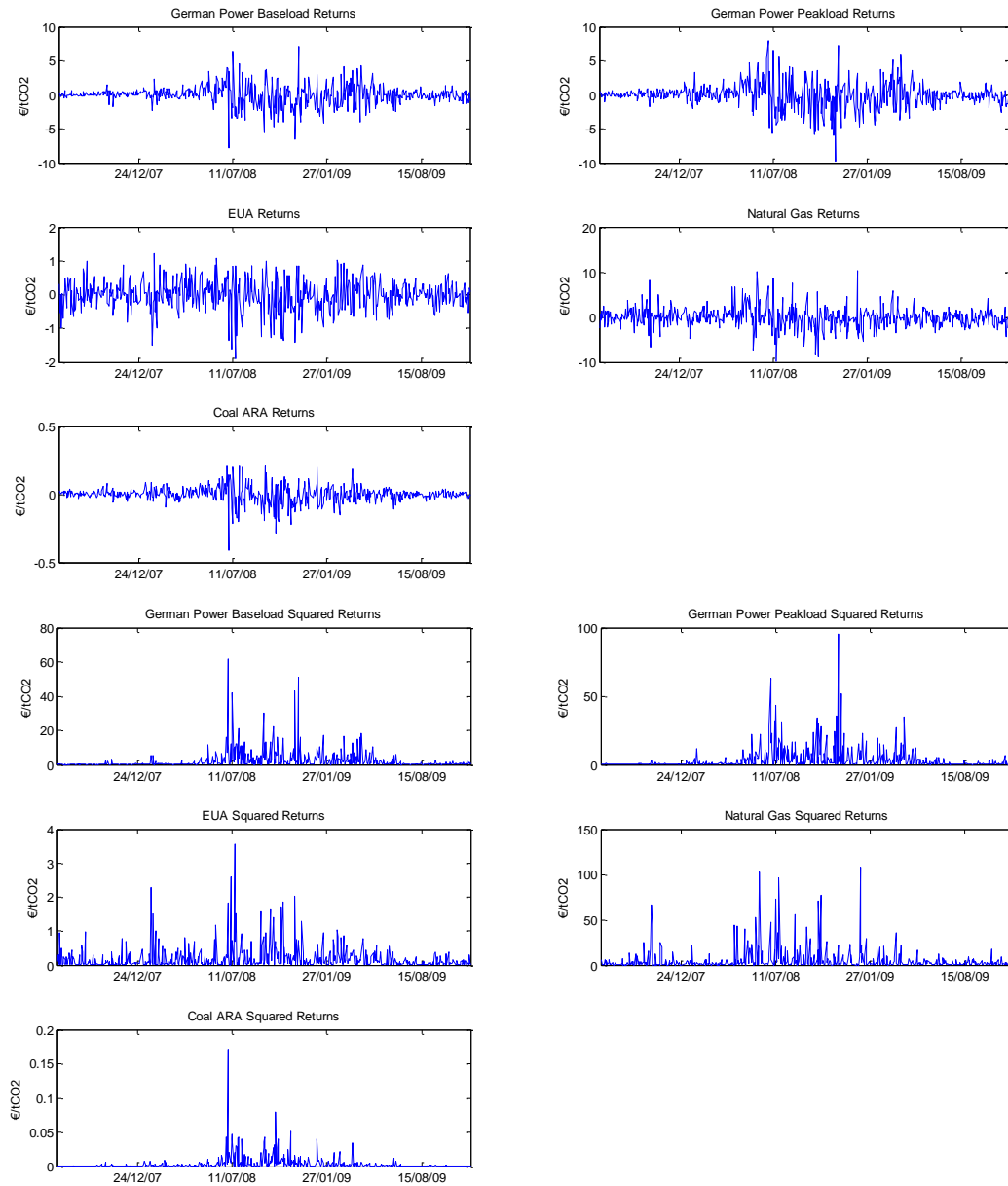


Figure 2.3: Log returns and squared log returns of futures contracts of power, natural gas, coal, and EUA futures

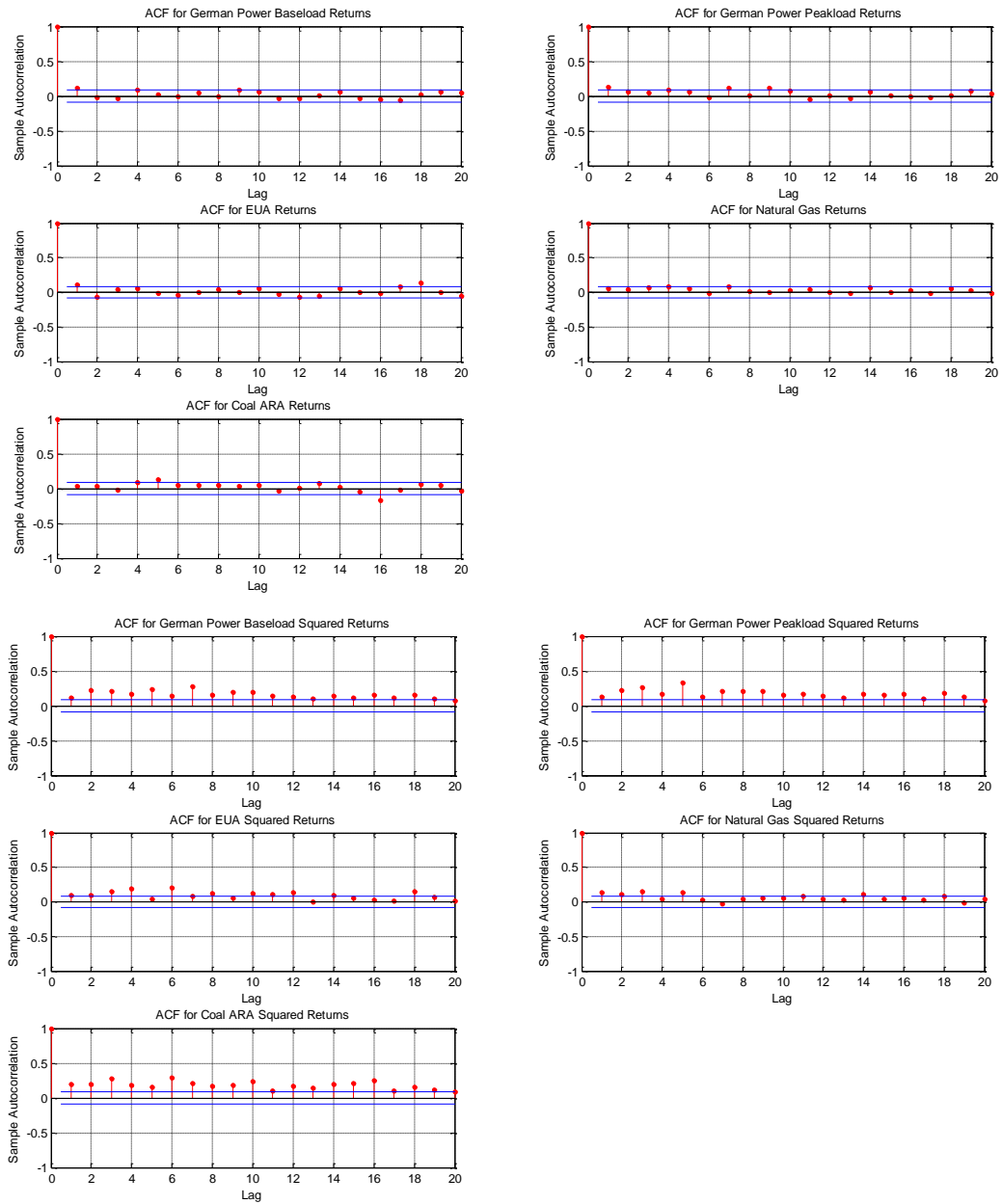


Figure 2.4: Autocorrelation functions for log returns and squared log returns of power, natural gas, coal, and EUA futures

2.5 Results

In this section we will describe the results of the empirical analysis of power, CO₂, gas, and coal returns. We will first present the results of the in-sample analysis studying the long-run equilibrium and short-run interactions between the endogenous variables. We will then calculate their impulse-response functions and analyze the impact of unexpected shocks on the commodity returns. Second, we will describe the results of the out-of-sample analysis, using the model forecasts for a dynamic portfolio application. Two empirical models are specified, including either the log return of baseload (BL) power or the log return of peakload (PL) power as endogenous variable.

2.5.1 In-sample analysis: Empirical interrelationships between energy and CO₂ returns

2.5.1.1 Cointegration testing

Before estimating our empirical model we have to test for the presence of cointegration relationships between the log prices in p_t . Cointegration between the log prices of power, CO₂, gas, and coal implies that one (or more) "long-run equilibrium" relation(s) exist between those prices. The number of cointegration relationships between the observable variables is indicated by the rank of the matrix Π in equation (2.27). To test for the number of cointegrating relations, we use the Johansen trace test introduced by Johansen (1995), which evaluates the following hypothesis:

$$H_0 : rk(\Pi) = m \quad \text{versus} \quad H_1 : rk(\Pi) > m,$$

where $m = 0, \dots, k - 1$ are the number of cointegration relations and k is the dimension of the vector of observable variables.⁹ In our case, since we have four variables in p_t , the maximum cointegration rank of Π is three. We estimate the model including an intercept in the VECM (we do not find statistically significant evidence of a trend) and one lag in the endogenous variables (the lag order was

⁹The eigenvalue test yields qualitatively similar results.

selected via Schwarz criterion). The results of the trace test are reported in Table 2.4, indicating that we can reject the null of no cointegration at the 1% significance level for the model with baseload power prices and at the 5% significance level for the model with peakload power prices, respectively. Since we cannot reject $H_0 : rk(\Pi) = 1$ for both models at any significance level, we include one cointegration relationship in the subsequent analysis. The empirical results presented in the following sections are based on the finding of a cointegration rank of one.

H_0	Test Statistic		Critical Values		
	Baseload specification (BL)	Peakload specification (PL)	1%	5%	10%
0	62.56	60.72	60.81	53.94	50.50
1	20.26	24.12	40.78	35.07	32.25
2	6.63	6.82	24.69	20.16	17.98
3	1.25	0.92	12.53	9.14	7.60

Table 2.4: Johansen trace test for $p_{e,t}$, $p_{a,t}$, $p_{g,t}$, $p_{c,t}$. Estimation including a constant and one lag in the VECM.

2.5.1.2 Long-run estimation analysis

The estimation results for the long-run relationship between electricity, emission allowances, natural gas, and coal prices are reported in Table 2.5, where the estimated cointegration coefficients ($\hat{\beta}$) represent the equilibrium relationship between the price of electricity and the prices of the other endogenous variables. In the baseload specification $p_{e,t}$ is given by:

$$p_{e,t} = \widehat{0.1954}p_{a,t} + \widehat{0.1711}p_{g,t} + \widehat{0.3299}p_{c,t} + z_t.$$

In the peakload specification $p_{e,t}$ is given by:

$$p_{e,t} = \widehat{0.1495}p_{a,t} + \widehat{0.3463}p_{g,t} + \widehat{0.2169}p_{c,t} + z_t.$$

In line with economic intuition the signs of the long-run coefficients in the above equations are positive, implying that an increase in one of the variables will have

a positive impact on electricity prices. As we model log prices we can directly interpret the long-run coefficients as price elasticities. Hence, a 1% increase, for instance, in natural gas prices would lead to a 0.17% increase in baseload electricity prices.

Interestingly, the long-run coefficient attached to natural gas prices is almost twice as high in the peakload specification than in the baseload specification, whereas the long-run coefficient attached to coal prices are considerably higher in the baseload specification than in the peakload specification. The reason could be that in periods of high electricity demand (i.e. peakload) the marginal plant is typically a gas-fired power plant, whereas in periods of baseload electricity demand the marginal power plant is typically coal-fired.

Baseload specification				Peakload specification			
$p_{e,t}$	$p_{a,t}$	$p_{g,t}$	$p_{c,t}$	$p_{e,t}$	$p_{a,t}$	$p_{g,t}$	$p_{c,t}$
1.000	-0.1954	-0.1711	-0.3299	1.000	-0.1495	-0.3463	-0.2169
-	[-9.519]	[-13.627]	[-15.950]	-	[-5.208]	[-19.731]	[-7.501]

Table 2.5: Estimated long-run coefficients of the cointegration relationship ($\hat{\beta}$) with t-ratios in brackets

Figure 2.5 provides a plot of the (*demeaned*) error-correction term z_t (also known as the "long-run equilibrium" error) in the baseload specification, representing the part of the power price $p_{e,t}$ that is not explained by the prices for EUA, gas, and coal $p_{a,t}$, $p_{g,t}$, $p_{c,t}$, respectively. As can be seen from Figure 2.5, the error-correction term is mean reverting and fluctuates around a zero mean. In other words, power prices have to decrease (increase) when they are too high (low) with respect to the "long-run" trend, given by the linear combination of $p_{e,t}$, $p_{a,t}$, $p_{g,t}$, and $p_{c,t}$. The error-correction term z_t also exhibits some jumps between July 2008 and February 2009, which corresponds to the period where the underlying commodity prices sharply increased and then collapsed.

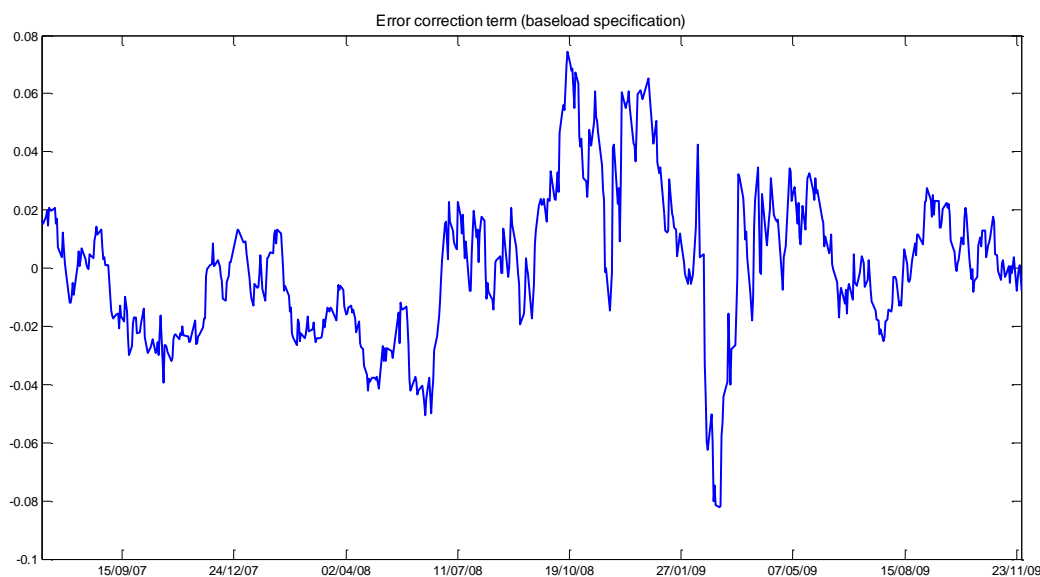


Figure 2.5: Error correction term (demeaned) in the baseload specification.

2.5.1.3 Short-run estimation analysis

The coefficients of the cointegration vector describe the long-run equilibrium relationship between the endogenous variables but do not provide information concerning the short-run dynamics of the system. The estimation results of the short-run dynamics for model specification 1 are presented in Table 2.6. In model specification 1, the exogenous variables include crude oil returns, earnings growth in the utility sector, 5-day moving averages of temperatures and rainfall deviations from their historical averages and squared terms of the latter two variables. For robustness, we also estimate the model with alternative specifications, where we vary the weather indicators included in the exogenous variable matrix. To save on space we provide the results of the alternative model specifications 2-4 in Appendix B.3.

In general, we find that the results of the short-run estimation analysis are quite robust across the different model specifications. However, the specifications including baseload electricity prices show a better performance in terms of the error-correction coefficients than the peakload specifications. This is in line with the results of the cointegration test, where the null of no cointegration relationship could only be rejected at the 10% level in the peakload specification. Besides the

error-correction coefficients, the short-run dynamics show very similar results for the baseload and peakload power specifications. While in the long run there is a considerably different relationship between power prices, fossil-fuel, and emission prices, depending on whether peakload or baseload power prices are considered, driven by the different types of power plants employed at the margin, we do not detect such a difference in the short run. This implies that in the short run the price determinants for baseload and peakload power are largely the same.

The first row in Table 2.6 reports the estimates for the error-correction coefficients ($\hat{\alpha}$) determining the speed of adjustment of the variables to the long-run equilibrium. The error-correction coefficients are statistically significant at the 5% level for electricity, emission allowances, and natural gas returns in the baseload specification and for electricity and emission allowances in the peakload specification. The error-correction coefficient is not statistically significant for coal returns, indicating that the long-run equilibrium error z_t does not have explanatory power for coal returns. This is consistent with the fact that the underlying coal price index of the futures contract is determined by demand and supply on the world market.

Concerning the short-run interrelationships between the returns of the endogenous variables ('Endo.' in Table 2.6), past electricity returns have predictability power for natural gas and coal returns in all model specifications. Moreover, EUA returns are explained by their own lagged returns, and gas returns have predictability power for coal returns. In addition, past EUA, gas, and coal returns do not have predictability power for electricity returns. This contrasts the findings of Bunn & Fezzi (2007) and Fell (2010) who have pointed out a significant impact of past gas and EUA returns on current electricity returns. Moreover, we find no significant short-run interactions between EUA returns and coal and gas returns, respectively.

Among the exogenous variables ('Exo.' in Table 2.6), past oil returns have predictability power at the 5% significance level for EUA returns. Moreover, EUA, coal, and gas returns are explained by lagged earnings growth in the utilities sector at the 5% and 10% significance level, respectively. Among the weather variables included in specification 1, past squared winter temperatures have predictabil-

ity power for EUA returns at the 5% significance level. Both past precipitation indices have predictability power for coal returns at the 10% significance level.

In our context interpreting the signs of the weather coefficients is not a simple task. Since we will use our model for forecasting, the conditional mean μ_t in (2.27) is strictly based on past information and thus on lagged exogenous variables. Therefore, we cannot consider the instantaneous effect of weather on the endogenous variables. Moreover, weather events generally might be less pronounced for prices of futures contracts than for spot contracts.

The contemporaneous interactions among the electricity, EUA, gas, and coal returns are described via the parameters attached to the fundamental innovations u_t ('Cont.' in Table 2.6). The coefficients attached to the fundamental error term of the electricity return equation $u_{e,t}$ are statistically significant at the 5% level in both model specifications. This implies that an unexpected shock on the electricity returns would lead to statistically significant instantaneous increases of electricity, EUA, natural gas, and coal returns. Moreover, the fundamental innovations related to emission allowance returns $u_{a,t}$ have a positive and statistically significant impact for electricity and EUA returns at the 5% level, and for natural gas returns at the 10% level. The fundamental innovations related to natural gas and coal returns $u_{g,t}$ and $u_{c,t}$ have explanatory power at the 5% level for their own returns, respectively. In addition, coal returns have a statistically significant contemporaneous impact at the 5% level on gas returns in the baseload specification. Finally, the last four rows in Table 2.6 ('Vol.') show that almost all ARCH and GARCH parameters are statistically significant at the 5% level indicating that the statistical innovations of the VECM are conditionally heteroscedastic.

2.5 Results

	Independent variables	Baseload specification 1				Peakload specification 1			
		$r_{e,t}$	$r_{a,t}$	$r_{g,t}$	$r_{c,t}$	$r_{e,t}$	$r_{a,t}$	$r_{g,t}$	$r_{c,t}$
Cons.	v	35.5836 [4.56]	53.7195 [3.69]	21.0960 [2.03]	19.5721 [1.55]	17.5394 [4.41]	32.8297 [3.77]	9.7926 [1.46]	7.9356 [1.08]
Endo. $\hat{\Gamma}_1$	z_{t-1}	-0.1223 [-4.56]	-0.1844 [-3.69]	-0.0724 [-2.03]	-0.0673 [-1.55]	-0.0658 [-4.42]	-0.1228 [-3.77]	-0.0366 [-1.46]	-0.0298 [-1.08]
	$r_{e,t-1}$	0.1180 [1.61]	-0.1094 [-0.58]	0.2586 [2.60]	0.2421 [2.50]	0.1121 [1.57]	-0.1191 [-0.58]	0.2074 [2.14]	0.2178 [2.08]
	$r_{a,t-1}$	0.0220 [0.68]	<i>0.1438</i> [1.91]	-0.0038 [-0.09]	-0.0370 [-0.80]	0.0174 [0.61]	0.1489 [2.0]	0.0178 [0.45]	-0.0190 [-0.42]
	$r_{g,t-1}$	0.0243 [0.65]	0.0400 [0.61]	-0.1048 [-1.49]	<i>0.1049</i> [1.72]	0.0495 [1.56]	0.0209 [0.32]	-0.0976 [-1.40]	<i>0.1097</i> [1.78]
	$r_{c,t-1}$	-0.0558 [-1.06]	-0.1289 [-1.30]	0.0045 [0.08]	-0.1065 [-1.55]	-0.0616 [-1.49]	-0.1310 [-1.44]	0.0395 [0.75]	-0.0802 [-1.26]
Exo. $\hat{\lambda}$	OIL_{t-1}	-0.0192 [-0.69]	-0.1008 [-2.19]	0.0507 [1.24]	0.0341 [0.75]	-0.0000 [-0.00]	-0.0993 [-2.17]	0.0493 [1.21]	0.0337 [0.74]
	EAR_{t-1}	-0.0087 [-0.88]	-0.0549 [-3.17]	<i>-0.0250</i> [-1.79]	-0.0293 [-2.46]	-0.0020 [-0.20]	-0.0521 [-3.14]	<i>-0.0228</i> [-1.69]	-0.0273 [-2.34]
	MAP_{t-1}	0.0033 [0.77]	0.0029 [0.35]	-0.0046 [-0.73]	<i>0.0106</i> [1.76]	0.0040 [1.09]	0.0044 [0.51]	-0.0041 [-0.65]	<i>0.0110</i> [1.81]
	$MATW_{t-1}$	-0.0300 [-0.76]	-0.0211 [-0.31]	-0.0396 [-0.67]	-0.0163 [-0.26]	-0.0349 [-1.14]	-0.0299 [-0.44]	-0.0353 [-0.61]	-0.0105 [-0.17]
	$MATS_{t-1}$	0.0019 [0.05]	0.0242 [0.37]	-0.0434 [-0.80]	0.0215 [0.36]	-0.0094 [-0.28]	0.0007 [0.01]	-0.0516 [-0.93]	0.0134 [0.22]
	MAP_{t-1}^2	0.0002 [1.26]	0.0003 [0.90]	0.0000 [0.21]	<i>0.0004</i> [1.79]	0.0001 [0.85]	0.0003 [0.84]	0.0000 [0.04]	0.0004 [1.62]
	$MATW_{t-1}^2$	-0.0032 [-0.34]	-0.0479 [-2.54]	-0.0178 [-1.06]	0.0042 [0.22]	0.0018 [0.26]	-0.0479 [-2.53]	-0.0181 [-1.07]	0.0040 [0.22]
	$MATS_{t-1}^2$	0.0125 [0.66]	0.0080 [0.26]	-0.0127 [-0.55]	0.0016 [0.06]	0.0161 [0.96]	0.0161 [0.31]	0.0095 [-0.56]	0.0009 [0.03]
Cont. $\hat{\mathbf{B}}$	$u_{e,t}$	0.7600 [4.84]	0.5811 [4.21]	0.5266 [4.66]	0.7372 [4.43]	0.5862 [3.58]	0.4866 [3.34]	0.4857 [3.54]	0.6965 [3.44]
	$u_{a,t}$	0.2282 [3.90]	2.2348 [6.60]	<i>0.1748</i> [1.78]	0.1598 [0.96]	0.1921 [3.45]	2.3110 [5.53]	0.2715 [2.58]	0.2223 [1.48]
	$u_{g,t}$	<i>0.0598</i> [1.69]	<i>0.2119</i> [1.89]	1.3825 [16.54]	0.0531 [0.68]	0.0278 [0.92]	0.1206 [1.15]	1.3867 [23.08]	0.1166 [1.37]
	$u_{c,t}$	0.0029 [0.05]	-0.0678 [-0.33]	0.2778 [2.83]	1.0386 [4.95]	<i>-0.1192</i> [-1.77]	-0.1366 [-0.70]	0.1774 [1.59]	1.0884 [6.59]
Vol. $\hat{\mathbf{C}}$	$\omega_{\bullet,t-1}$	0.8839 [9.80]	0.8417 [5.46]	0.9042 [4.76]	0.9476 [4.38]	0.8929 [6.68]	0.8578 [5.18]	0.1680 [0.96]	0.9366 [6.56]
	$v_{\bullet,t-1}^2$	0.1067 [5.05]	0.1232 [2.06]	0.0464 [0.11]	<i>0.0461</i> [1.76]	0.0991 [3.83]	0.1174 [2.23]	0.1710 [2.88]	0.0513 [2.39]

Table 2.6: VECM with orthogonal GARCH errors, specification 1: mean/variance equations and contemporaneous coefficients. OLS estimation of the mean equation with heteroscedasticity consistent t-ratios in brackets. Maximum likelihood estimation of the contemporaneous coefficients and variance coefficients with t-ratios in brackets. **Bold** (*italic*) entries indicate significance of the coefficients at the 5% (10%) significance level.

Figure 2.6 shows plots of the time-varying volatilities of electricity, EUA, gas, and coal returns in baseload specification 1. Similar to the plots of the log returns (Figure 2.3), the time-varying volatility plots display periods of higher and lower volatility and volatility clustering. In the power, EUA, and coal markets, the volatility is rather low in the beginning of the sample period, then increases in the second half of the sample, and declines towards the end of the sample period. The increase in volatility falls into the period of the global financial crisis, which started in the late summer of 2007 and lasted until (at least) spring 2009. The natural gas market, apart from the higher volatility during the financial crisis, also displays a peak in volatility in the first half and increasing volatility towards the end of the sample period. Moreover, the occurrence of volatility seems to coincide across the markets, which is particularly evident in the power and coal markets.

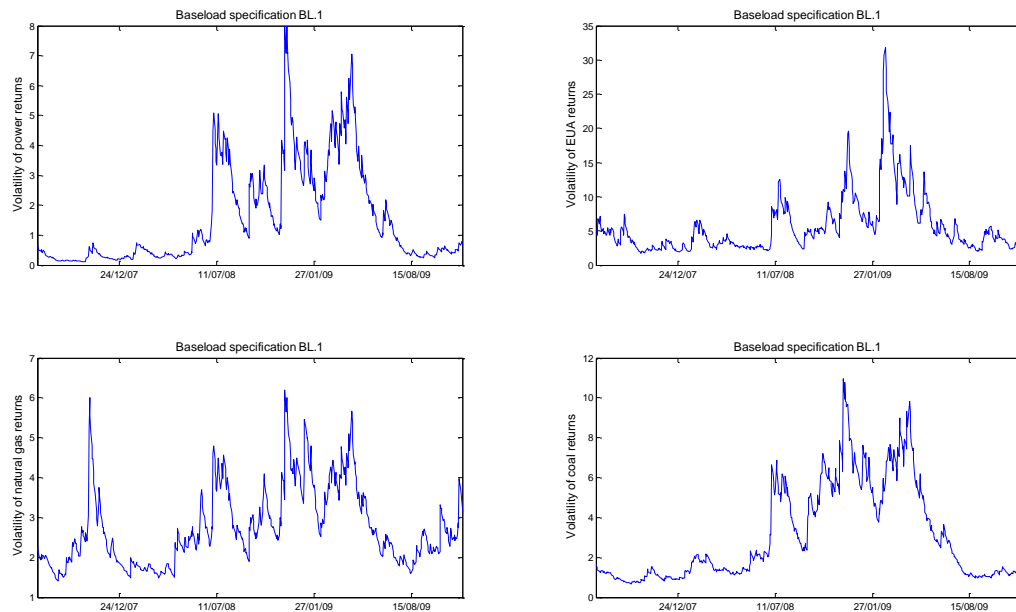


Figure 2.6: Time-varying volatilities of electricity, EUA, natural gas, and coal returns in baseload specification 1.

In addition, Figure 2.7 displays the time-varying correlations amongst the statistical innovations $\hat{\varepsilon}_t$. All correlations are positive and, as expected, the highest correlations can be observed between electricity returns and returns of

the three "input factors" coal, gas, and emissions allowances. The lowest time-varying correlations are found between EUA and gas returns, and EUA and coal returns, respectively. Moreover, the correlations between EUA and gas returns and EUA and coal returns move closely together. The same co-movement holds for the correlations between power and gas returns, and gas and coal returns, respectively. In addition, there are large variations in the correlations over time. For instance, the correlation between power and coal returns varies considerably (lying between 0.3 and almost 0.9), whereas the correlation between power and EUA returns remains relatively stable (ranging between 0.5 and 0.72). The time-varying correlations for the peakload specification 1 are very similar, except that the correlation between power and coal is significantly lower than in the baseload specification. As was already mentioned before, this could be due to the fact that a stronger relationship exists between baseload power and coal returns than between peakload power and coal returns.

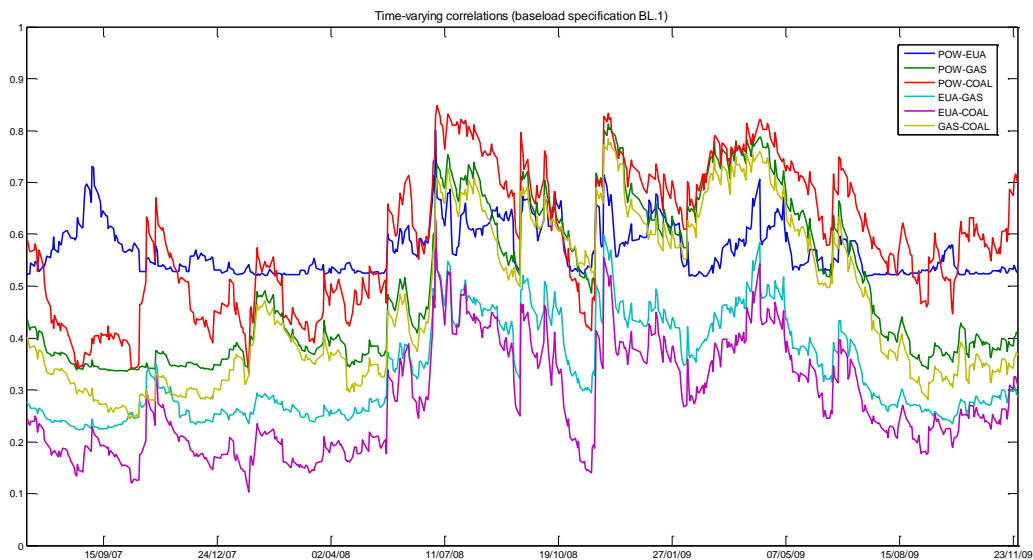


Figure 2.7: Time-varying correlations between electricity, EUA, natural gas, and coal returns in baseload specification BL.1.

2.5.1.4 Impulse-response analysis

In the following, we will describe the responses of electricity, emission allowance, natural gas, and coal returns to unexpected one-standard-deviation shocks entering the system through the fundamental innovations $u_{\bullet,t}$ with $\bullet = e, a, g, c$ given by equation (2.7). The unconditional variances of the fundamental innovations are normalized, i.e. $Var[u_{\bullet,t}] = 1$. Therefore, we can interpret the impulse responses as unit changes of the endogenous variables following a one-unit shock on the corresponding fundamental residuals.

The dynamic responses of all variables to the fundamental shocks are shown in Figure 2.8 for baseload specification 1 (BL.1), where the four plots in Figure 2.8 display the impulse-response functions (IRF) of baseload power returns, emission allowance returns, natural gas returns, and coal returns to shocks on the fundamental innovations $u_{e,t}$, $u_{a,t}$, $u_{g,t}$, and $u_{c,t}$, respectively, under identification through heteroscedasticity (IH).¹⁰ Following our explanation in Section 2.2.2, the values of the coefficients in the contemporaneous coefficient matrix $\widehat{\mathbf{B}}$ determine the initial impacts of one-time shocks at horizon $h = 0$ on the endogenous variables, whereas at higher horizons $h > 0$ the responses are determined by the short-run dynamics of the VECM.

A common feature of all plots in Figure 2.8 is that a particular commodity's return generally shows the strongest instantaneous reaction to shocks on its own fundamental innovations, respectively. Apart from the strong instantaneous reactions to their "own" fundamental shocks, EUA, gas, and coal returns exhibit the strongest instantaneous response to a shock on the fundamental innovations related to power returns $u_{e,t}$. This indicates that the contemporaneous interactions between returns of the output electricity and returns of its three inputs coal, gas, and emission allowances are higher than the contemporaneous interactions among the returns of the inputs. Finally, all the shocks are transitory and fade out after approximately three days.

As can be noted from the first plot in Figure 2.8, power returns exhibit a positive instantaneous reaction to a one-unit shock on the fundamental innovations related to EUA returns, which is statistically significant at the 5% level.

¹⁰The impulse responses obtained for the peakload specification PL.1 are very similar.

By contrast, power returns show almost no sizable reaction to shocks on gas and coal returns. The impulse responses of EUA returns illustrated in the second plot in Figure 2.8 show a positive instantaneous reaction to a one-time shock on electricity returns, which is statistically significant at the 5% level. Similarly, an unexpected shock on gas returns leads to a positive contemporaneous reaction of EUA returns, which is statistically significant at the 10% level. By contrast, EUA returns have a negative instantaneous reaction to a one-time shock on coal returns. This observation may be interesting from a policy perspective since it indicates that, due to the fixed supply of emission allowances, an increase in the coal price may be accompanied by a decrease in the EUA price (due to lower demand for EUAs).¹¹ Moreover, this would imply that the negative reaction of EUA prices mitigates the effect of increasing coal prices on the power price. By contrast, the reason why the reaction of EUA returns to shocks on gas returns is positive may be that increasing gas prices lead to increased demand for coal (i.e. there is fuel switching from gas to coal), thus increasing demand and prices of EUAs. In the third plot in Figure 2.8 natural gas returns exhibit a positive instantaneous response to fundamental shocks on both power and coal returns (statistically significant at the 5% level) and EUA returns (statistically significant at the 10% level). Finally, the fourth plot in Figure 2.8 illustrates that coal returns have a positive response to shocks on all the endogenous variables, where the instantaneous reactions to shocks on power and coal returns are statistically significant at the 5% level.

¹¹Recall that a negative return r_t implies that the current price in t is lower than the price in $t - 1$.

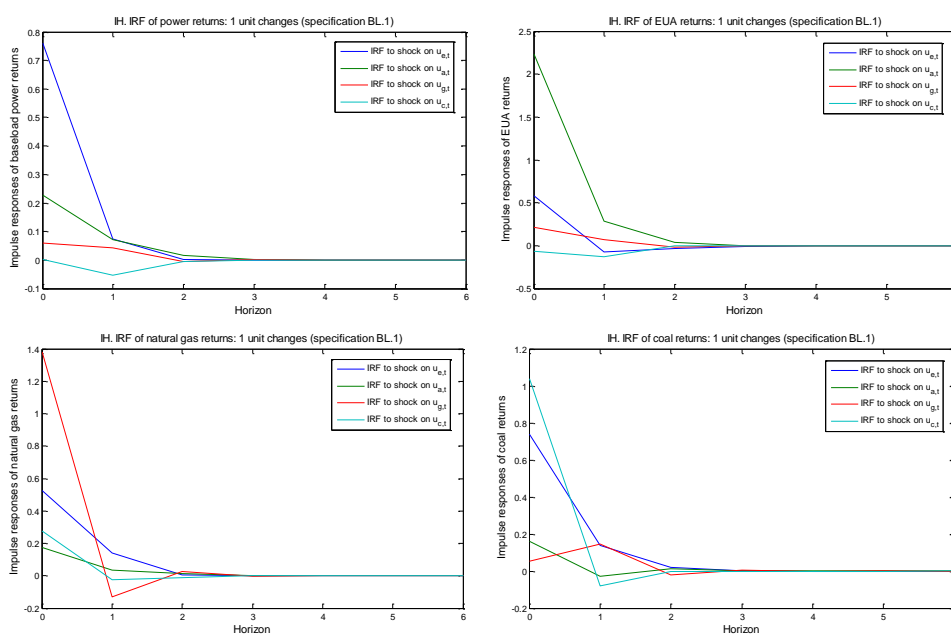


Figure 2.8: Impulse-response functions (IRF) under identification through heteroscedasticity (IH) in baseload specification 1. The first, second, third, and fourth plot illustrate the impulse responses of baseload electricity, EUA, natural gas, and coal returns, respectively, to one-time shocks on the fundamental innovations $u_t = (u_{e,t}, u_{a,t}, u_{g,t}, u_{c,t})'$.

2.5.2 Out-of-sample analysis: Dynamic portfolio allocation

This section will present the results of the out-of-sample analysis, where we use the forecasted returns and covariances given by (2.37) and (2.38) to perform the dynamic portfolio allocation analysis described in Section 2.3. The present portfolio analysis builds upon a finance-based approach and does not take into account factors that typically play an important role in energy markets, such as capacity constraints, delivery and purchase obligations and times. These issues would need to be considered and would add complexity, for instance, in the case of an energy company wishing to optimize its energy portfolio. We perform the out-of-sample analysis with model specification 1 discussed in the previous sections. The reason for not considering the other specifications is that the matrix of exogenous variables contains too many zero entries (due to the dummy variables and the extreme-weather variables) and thus it is not feasible to use these specifications for forecasting. This problem may be solved by obtaining a longer sample period with sufficient non-zero entries in the matrix of exogenous variables.

2.5.2.1 Performance of dynamic trading strategies

In the following we will describe the economic performance of the dynamic trading strategies for the alternative investment objectives presented in Section 2.3.2 (minimum volatility, maximum return, and maximum utility). We will also consider different portfolio rebalancing horizons $h = 1, 5, 10$, where h is the number of working days after which the weights of the assets held in the portfolio are readjusted (i.e. daily, weekly, and bi-weekly).¹²

In our baseline scenario we calculate the portfolio performance measures using an annualized risk-free rate of $i_f = 5\%$, an annualized target return of $\mu_p^* = 8\%$ for the minimum-volatility strategy, an annualized target variance of $\sigma_p^* = 12\%$ for the maximum-return strategy, and a coefficient of absolute risk aversion of $\gamma = 6$ for the maximum-utility strategy.¹³ The benchmark portfolio used to calculate

¹²Our analysis assumes that there are no transaction costs associated with the adjustment of the portfolio. In the presence of transaction costs, the results for the dynamic trading strategies might change.

¹³This is in line with the parameter values used in Han (2006).

the $\mathcal{M}2$ measure consists of a buy-and-hold strategy, implying that the optimal portfolio weights are set only once based on the estimated in-sample means and covariances of the energy returns and there is no portfolio rebalancing. The performance results of the dynamic trading strategies are presented in Table 2.7 for two in-sample estimation periods ($T^* = 200$ and $T^* = 400$).

The positive values of the ex-ante and ex-post Sharpe ratios (\mathcal{SR}) in Table 2.7 indicate that profitable trading strategies can be generated based on our energy portfolio with the underlying VECM-OGARCH model. Since for all the commodities except for coal, the mean returns were negative over the sample period, this indicates that holding an optimal portfolio of the commodities improves the performance compared to investing in a single commodity. Moreover, since the ex-ante \mathcal{SR} 's are based on the forecasted portfolio mean and standard deviation and the ex-post \mathcal{SR} 's on their actual realizations, the former generally overestimate the profitability of a given trading strategy. In terms of the relative performance of the different trading strategies, strategies 2 and 3 (maximum return and maximum utility) outperform the minimum-volatility strategy. However, the results for the $\mathcal{M}2$ measure in the last column of Table 2.7, describing the relative performance of the dynamic trading strategies over a static strategy, indicate that under the baseline calibration, the dynamic portfolio rebalancing does not lead to an improved performance compared to a simple buy-and-hold strategy. This result may be due to the generally high level of volatility of the energy returns in the present sample period. Moreover, the results depend crucially on the underlying choices of the target portfolio return and covariance, the risk-free rate, and the coefficient of risk-aversion. Therefore, we perform a sensitivity analysis for alternative values of these parameters in Section 2.5.2.3.

2.5 Results

Investor's objective	Horizon	Ex-ante \mathcal{SR}	Ex-post \mathcal{SR}	$\mathcal{M}2$
In-sample estimation period: $T^* = 200$				
Min. volatility (Strategy 1)	1	1.074 (1.199)	-0.000 (-0.138)	-0.014 (-0.022)
	5	0.897 (1.245)	0.106 (0.218)	-0.059 (-0.042)
	10	0.981 (1.388)	0.143 (0.283)	-0.109 (-0.097)
Max. expected return (Strategy 2)	1	1.380 (1.551)	0.043 (0.055)	-0.009 (-0.009)
	5	1.420 (1.663)	0.085 (0.359)	-0.079 (-0.048)
	10	1.610 (1.943)	0.139 (0.463)	-0.210 (-0.203)
Max. expected utility (Strategy 3)	1	1.669 (1.811)	0.079 (0.129)	-0.005 (-0.004)
	5	2.010 (2.111)	0.073 (0.464)	-0.015 (-0.011)
	10	2.390 (2.621)	0.133 (0.527)	-0.045 (-0.055)
In-sample estimation period: $T^* = 400$				
Min. volatility (Strategy 1)	1	0.426 (0.418)	-0.141 (-0.132)	-0.026 (-0.025)
	5	0.281 (0.290)	-0.012 (0.021)	-0.053 (-0.049)
	10	0.268 (0.420)	-0.076 (0.043)	-0.130 (-0.093)
Max. expected return (Strategy 2)	1	0.562 (0.555)	-0.088 (-0.074)	-0.009 (-0.009)
	5	0.446 (0.448)	0.104 (0.073)	-0.026 (-0.034)
	10	0.404 (0.420)	0.150 (0.068)	-0.088 (-0.123)
Max. expected utility (Strategy 3)	1	0.804 (0.760)	-0.096 (-0.083)	-0.003 (-0.003)
	5	0.759 (0.809)	0.017 (-0.065)	-0.008 (-0.010)
	10	0.510 (0.538)	0.257 (0.074)	-0.004 (-0.015)

Table 2.7: Ex-ante and ex-post Sharpe ratios and Modigliani risk-adjusted performance measure for different in-sample estimation periods and rebalancing horizons in baseload specification BL.1 (PL.1) with $i_f = 5\%$, $\mu_p^* = 8\%$, $\sigma_p^* = 12\%$, $\gamma = 6$. Horizons for portfolio rebalancing in working days: $h = 1, 5, 10$.

2.5.2.2 Time-varying portfolio weights

Figure 2.9 illustrates the optimal time-varying portfolio weights for the baseline scenario with $T^* = 200$. In the figure, positive (negative) weights imply that the investor goes long (short) in the respective commodity, i.e. he or she buys (sells) the corresponding futures contract. At each point in time, the sum of all portfolio weights must equal 1 and hence, the sum of commodity weights $\sum w_{\bullet,t}$ with $\bullet = e, a, g, c$ represents the share invested in the risky portfolio and $(1 - \sum w_{\bullet,t})$ is the share invested in the risk-free asset at time t .

Several interesting observations arise from the plots of optimal portfolio weights. First, in the minimum-volatility strategy (strategy 1) the share of the portfolio invested in the risky energy commodities is lower than under the other trading strategies for all rebalancing horizons and hence, a larger share is invested in the risk-free asset. This is an intuitive result given that there is a considerable amount of volatility in the energy returns (see Figure 2.6). Second, the portfolio weights of the risky commodities increase with the rebalancing horizon for all three trading strategies suggesting that the model exploits long-run information (presumably via z_t). Finally, among the risky commodities the highest absolute portfolio weights are attached to power futures and these weights also exhibit a higher variation compared to the portfolio weights of other energy commodities.

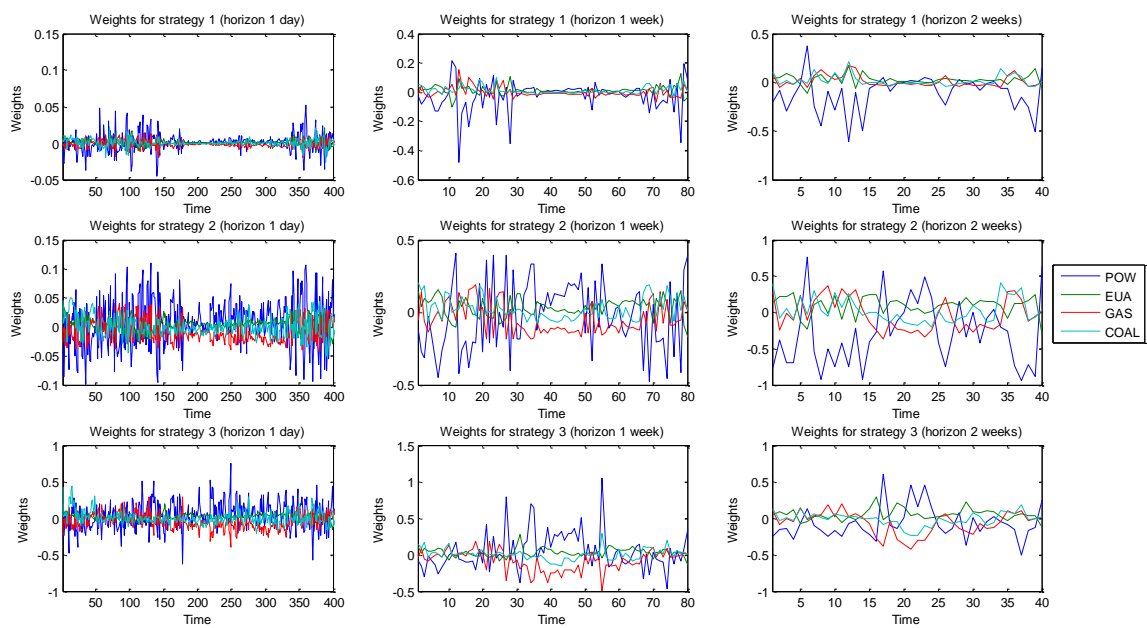


Figure 2.9: Optimal portfolio weights for different trading strategies at various rebalancing horizons and $T^* = 200$ in baseload specification BL.1. Strategy 1: Min. volatility, Strategy 2: Max. expected return, Strategy 3: Max. expected utility. Horizons for portfolio rebalancing: 1 day, 1 week, 2 weeks. Positive (negative) weights imply that the investor goes long (short) in the respective commodity.

2.5.2.3 Sensitivity analysis

We test the sensitivity of the performance of the different trading strategies with respect to the parameters assigned to the risk-free rate, the target portfolio return, the target portfolio volatility, the risk-aversion coefficient, and the horizon for portfolio rebalancing. For robustness we perform the sensitivity analysis for two alternative in-sample estimation periods. The results of the portfolio performance in terms of the $\mathcal{M}2$ measure are illustrated in Figures 2.10 and 2.11 for $T^* = 200$ and $T^* = 400$, respectively. Note that varying the risk-free rate impacts on all trading strategies, while varying the target return, the target volatility, and the risk-aversion coefficient only impacts on strategy 1 (min. volatility), 2 (max. return), and 3 (max. utility), respectively. In general, varying the parameter values and the rebalancing horizon can lead to quite considerable changes in the value of $\mathcal{M}2$ for a given trading strategy.

In Figures 2.10 and 2.11, the upper panel illustrates the sensitivity of $\mathcal{M}2$ with respect to the risk-free rate for the three trading strategies. The plots in the upper panel of both figures show that increasing the risk-free rate i_f leads to an improvement of the performance of all dynamic trading strategies compared to a static strategy for both in-sample estimation periods. The only exception is given by strategies 2 and 3, where the relative performance of dynamic trading decreases in i_f at higher rebalancing horizons ($h > 7$) and $T^* = 200$.

The plots in the lower panel of both figures illustrate the sensitivity of $\mathcal{M}2$ with respect to the target portfolio return, the target portfolio volatility, and the coefficient of risk aversion, respectively. In the minimum volatility strategy, $\mathcal{M}2$ decreases in the target return and increases in the rebalancing horizon for both in-sample estimation periods. A similar result arises for the maximum return strategy. Finally, under the maximum utility strategy, $\mathcal{M}2$ increases in the risk-aversion coefficient and decreases in the rebalancing horizon.

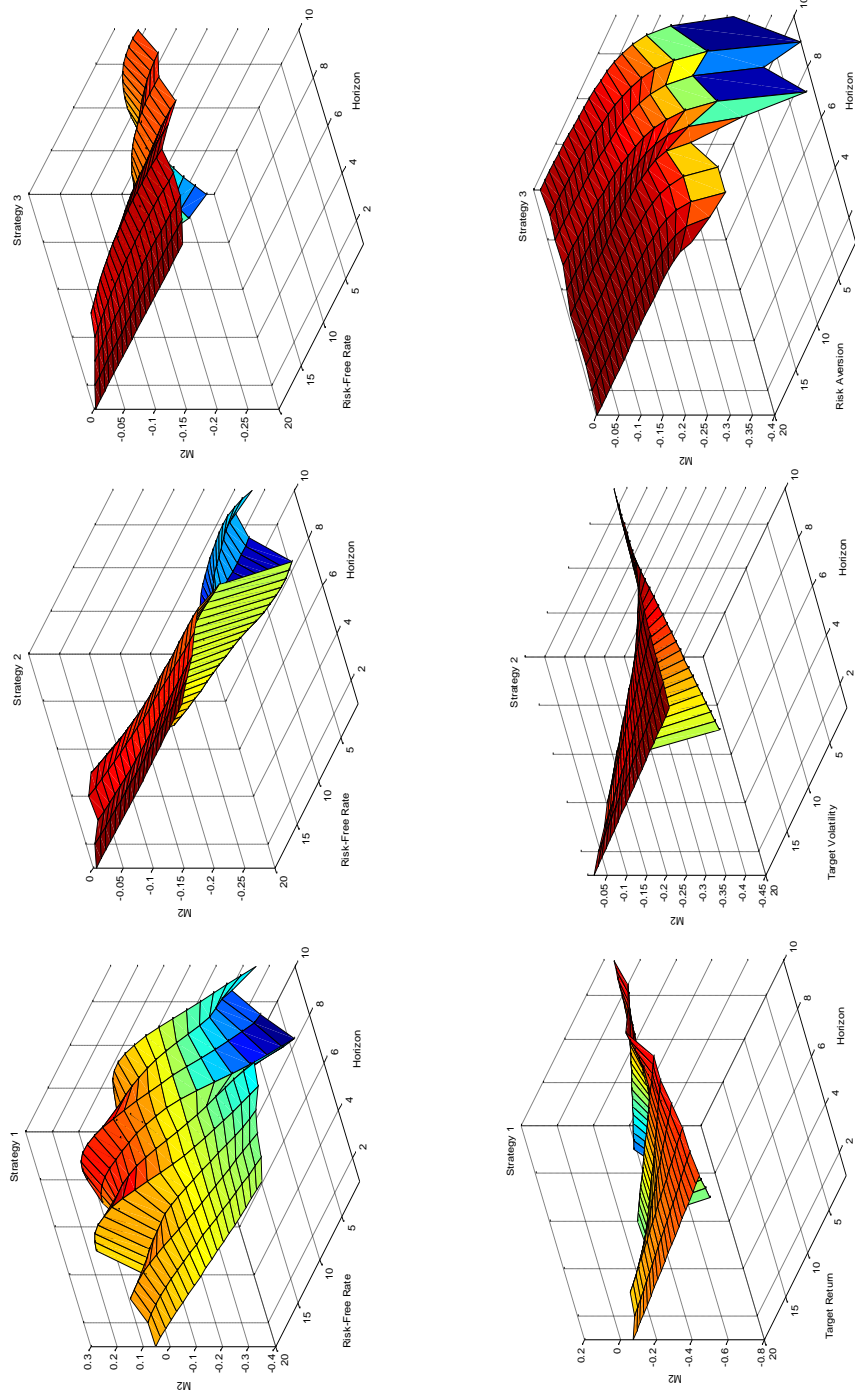


Figure 2.10: Sensitivity of M2 with respect to different parameter values of the risk-free rate, the target portfolio return, the target portfolio volatility, and the risk-aversion coefficient for $T^* = 200$ in baseload specification BL.1.

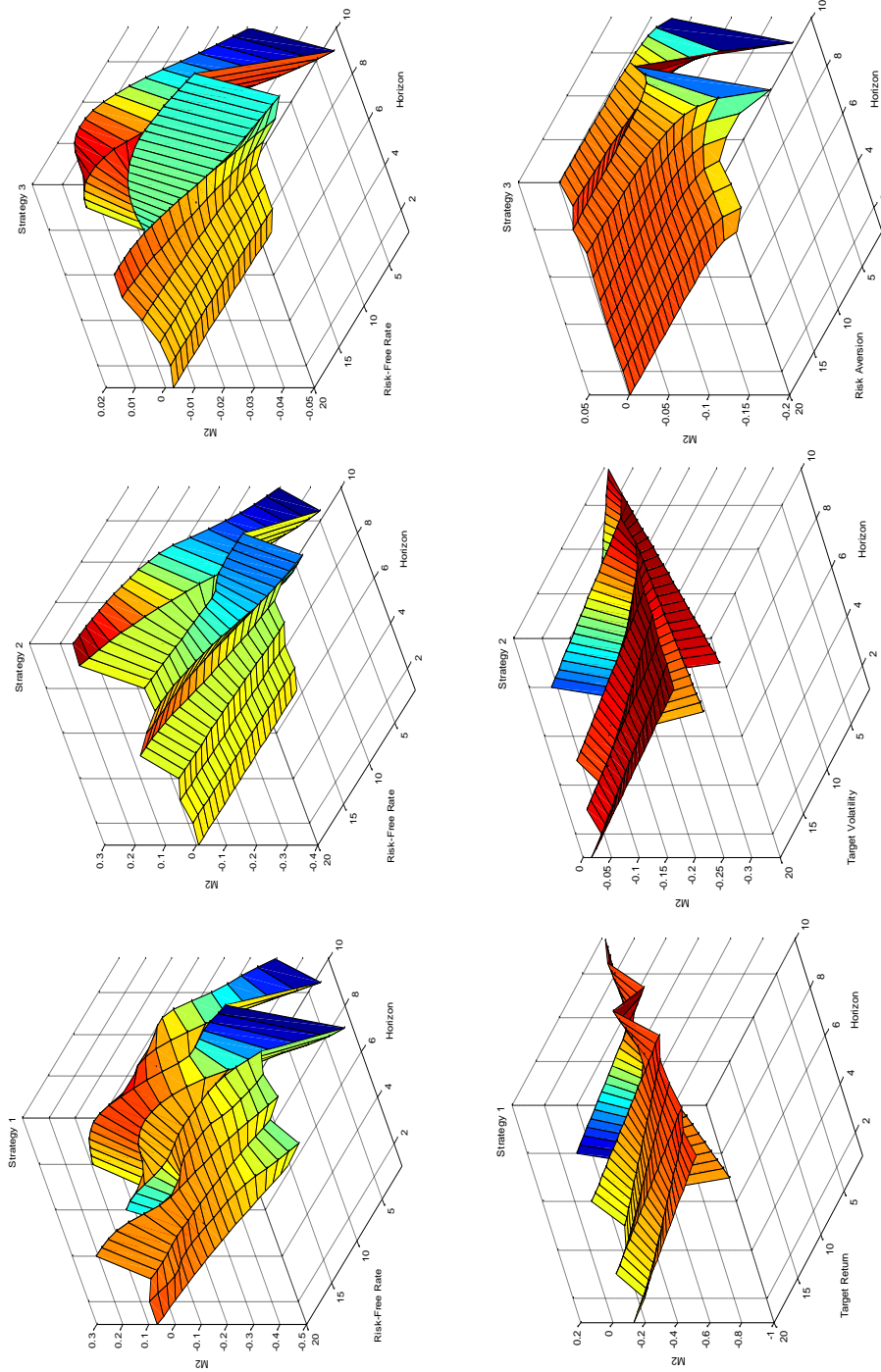


Figure 2.11: Sensitivity of M2 with respect to different parameter values of the risk-free rate, the target portfolio return, and the target portfolio volatility, and the risk-aversion coefficient for $T^* = 400$ in baseload specification BL.1.

2.6 Concluding remarks

In this chapter we have set up a VECM model with orthogonalized GARCH errors to analyze the interactions between electricity, coal, natural gas, and European emission allowances futures. The VECM takes into account the "long-run equilibrium" relationship between electricity prices and prices of its three input factors, the short-run interactions between the commodity returns, and the influence of exogenous variables such as weather indices, crude oil returns, and economic growth. In addition, the orthogonal GARCH structure of the residuals allows for the identification of contemporaneous interactions between the commodities.

Our empirical results indicate that power, natural gas, coal, and emission allowance prices are cointegrated, implying that a "long-run equilibrium" relationship exists between these prices. In addition, the estimated elasticity of the natural gas price with respect to the peakload power price is roughly twice as high than the elasticity with respect to the baseload power price, whereas the opposite holds for the elasticity of the coal price with respect to the power price. This may result from the fact that gas-fired power plants are at the margin in periods of high electricity demand and coal-fired power plants are at the margin in periods of normal or low electricity demand.

In the short-run, we find that past EUA and crude oil returns, earnings growth, and winter temperatures have predictability power for EUA returns. Past electricity returns and earnings growth have predictability power for natural gas returns, while past electricity and gas returns, earnings growth, and precipitation have predictability power for coal returns. In contrast to the findings by Bunn & Fezzi (2007) and Fell (2010), electricity returns seem to be largely unaffected by the short-run dynamics in both the baseload and the peakload specification. In addition, the ARCH and GARCH parameters are highly significant, indicating that the time-varying volatility structure of the residuals is an essential component in models of energy and CO₂ returns. Moreover, we find that almost all contemporaneous interactions between energy and CO₂ returns are statistically significant. The impulse-response functions of the endogenous variables show that the instantaneous reactions of EUA, gas, and coal returns are particularly

2.6 Concluding remarks

strong with respect to an unexpected shock on power returns. By contrast, unexpected shocks on gas and coal returns do not seem to contemporaneously affect electricity returns. In the case of a shock on coal returns, this may be due to the negative instantaneous reaction of EUA returns, which may mitigate the overall impact of the shock on electricity returns. This dampening effect on electricity returns could arise when increasing production costs of coal-based electricity decrease demand and thus prices of emission allowances. By contrast, the positive instantaneous reaction of EUA returns to a shock on gas returns may hint at fuel-switching from natural gas to more emission-intensive coal. Moreover, we find that the dynamic interactions between energy and CO₂ returns in the short run are very similar independently of whether we use baseload or peakload power returns. This indicates that peakload and baseload power prices are driven by the same factors in the short run.

In the out-of-sample portfolio application, we find that our model can generate profitable trading strategies for different investment objectives and rebalancing horizons, although the dynamic strategies cannot generally outperform a static buy-and-hold strategy. Moreover, the results of our sensitivity analysis indicate that increasing the risk-free market rate and the investor's coefficient of risk-aversion both improve the relative performance of the dynamic strategies over a static strategy, while increasing the target return and target volatility of the portfolio both decrease the relative performance of the dynamic strategies.

It is important to keep in mind that the sample covers a period with sharply increasing energy prices in 2007 and the first half of 2008 followed by dramatic price decreases during the economic slowdown in the second half of 2008 and 2009. In our sample energy and CO₂ returns are thus characterized by a high level of volatility. Therefore, it would be interesting to compare the present results with those obtained from a larger sample period. A larger sample with more observations would also enable us to use other weather indices in the forecasting procedure. Moreover, future research on dynamic portfolio allocation could incorporate issues that typically play an important role in energy markets such as capacity constraints, delivery and purchase obligations and times.

Chapter 3

Emission allowance trading and market power

3.1 Introduction

Emissions trading schemes have become increasingly popular in recent years. One of the first comprehensive and successful trading schemes was the SO₂ emission trading scheme established in the United States (U.S.) in 1990 under the Acid Rain Program of the Clean Air Act (Clean Air Act Amendments 1990). In 1997, the adoption of the Kyoto Protocol was the first attempt to implement an international trading scheme for greenhouse gas emissions covering the majority of industrialized countries. It allows countries that have committed to reduce their CO₂ emissions to trade emission allowances with one another and use them to meet part of their reduction target. In 2005 the European Union launched the European Emission Trading Scheme (EU-ETS) for combating CO₂ emissions, covering roughly 50 percent of total CO₂ emissions in the EU. Under this scheme, firms from designated sectors can trade CO₂ emissions allowances across the entire European Union. Other emissions trading schemes implemented at present include the New South Wales Greenhouse Gas Abatement Scheme in Australia, the Regional Greenhouse Gas Initiative (RGGI) in ten Northeast and Mid-Atlantic States of the U.S., the Japanese Voluntary Emission Trading Scheme, and the New Zealand Emission Trading Scheme. Tradable emission allowances are also popular for managing smaller-scale pollution problems such as local or regional

water and air pollution. Prominent examples include the particulate emission allowance market established in Santiago de Chile in 1992 and the Hunter river salinity trading scheme operating in New South Wales, Australia, since 1995.

Under a system of tradable emission allowances, the emission target is achieved by setting a cap on the total amount of pollution and distributing a corresponding number of emission allowances. Firms participating in a tradable allowance scheme have to hold an allowance for each unit of pollutant they emit. If a firm's emissions are higher than the number of allowances it holds, it either has to carry out measures to reduce pollution or buy additional allowances in the allowance market. This decision is based on a comparison between the marginal abatement cost (i.e. the cost of reducing an additional unit of pollution) and the market price for emission allowances (i.e. the cost of emitting an additional unit of pollution). The price for pollution is then determined through supply and demand in the emission allowance market.

Companies obliged to reduce emissions by participating in emission trading schemes face additional costs because emissions are thus turned from a free into a costly production factor. This alters the production decisions of companies and, to the extent that they are able to pass on the additional costs to final goods prices, also affects the consumption choices of consumers. In principle, this is a desirable outcome because allowance prices should (ideally) reflect the social cost of pollution that would not be accounted for otherwise. However, improper implementation of tradable allowance schemes may give rise to distortions that harm both the effectiveness and the cost efficiency of such a scheme.

The aim of this chapter is to evaluate tradable emission allowance schemes with special reference to their anti-competitive effects due to market power on either the allowance market, the output market, or both. In a nutshell, there are three main sources for anti-competitive effects arising from emission allowance trading. First, large firms may exercise market power on the allowance market by holding down supply or suppressing demand in order to manipulate prices to their advantage. Second, firms may abuse the allowance market to put other firms, with whom they compete on the output market, at a competitive disadvantage. The strongest form of such abuse is market foreclosure. Finally, there may be

3.2 The economic efficiency of emissions trading

other distortions and abuses caused by special or ill-defined rules on the allowance market or other markets.

The remainder of this chapter is organized as follows. In the next section we will briefly explain the economic efficiency of emissions trading in the absence of market imperfections. In Sections 3.3 and 3.4 we will then highlight how market power may be exercised on allowance markets under free allocation and auctioning, respectively. Section 3.5 will revolve around the potential for cartel agreements on allowance markets. In Section 3.6 we will then turn to the issue of how allowance markets may be manipulated to gain advantage on the output market. The empirical evidence for the abuse of market power on allowance markets will be described in Section 3.7. In particular, we will analyze two prominent cases of (alleged) allowance market abuse by power utilities in Germany and California. Finally, Section 3.8 will provide a summary of the main results and some policy conclusions.

3.2 The economic efficiency of emissions trading

A major advantage of market-based policies such as emissions trading over most command-and-control regulations is that the former policies usually have a better performance in terms of their economic efficiency. In general, economic efficiency refers to the ability of a policy instrument to achieve a certain aggregate emission target at minimal cost. This is the case when each polluting entity bears the same cost in abating the last unit of pollution. In other words, economic efficiency requires that marginal abatement costs are equalized across all polluters. When the aggregate emission target is subject to a cost-benefit analysis, the economically efficient outcome is achieved when the total economic cost, consisting of abatement cost plus social damage from pollution, is minimized. While marginal abatement cost represents the cost of abating one additional unit of pollution, marginal damage reflects the damage of one additional unit of pollution emitted. The optimal emission level, and hence the optimal allocation of abatement effort, requires the marginal abatement cost to equal the marginal social damage of pollution. Therefore, both an increase of emissions beyond the optimal point and above-optimal abatement lead to total costs that are higher than the optimum.

3.2 The economic efficiency of emissions trading

If it is properly implemented (especially if the regulator issues the optimal number of tradable allowances) and if each polluter is relatively small compared to the whole market, a system of tradable emission allowances will lead to cost-efficient emission reduction. The condition that firms be small is an important one, because to achieve efficiency firms must take the market price for allowances as given or at least must believe that they are unable to influence this price by holding back or selling a large number of allowances. Figure 3.1 exemplifies the underlying mechanism for two polluting firms. The two firms exhibit different marginal abatement costs represented by the curves MAC_1 and MAC_2 , respectively. The marginal abatement cost curves are decreasing, reflecting the fact that it becomes more and more expensive to further reduce emissions. The positively sloped marginal damage curve implies that marginal damage increases in the level of pollution. The optimal, cost-minimizing emission level E^* then lies at the intersection of the aggregate marginal abatement cost and the marginal damage curve. This level E^* corresponds to the total quantity of emission allowances L the emission trading authority allocates to the two firms. Assuming perfect competition, the trading of allowances among the two firms gives rise to a uniform allowance price. Both firms compare the allowance price with their marginal abatement cost and buy (sell) allowances as long as the price is below (exceeds) their marginal abatement cost. In market equilibrium, at price p^* , firm 1 and firm 2 demand allowances corresponding to the emission levels e_1 and e_2 , respectively. Therefore, cost-efficiency requires that marginal abatement costs be equal for all emitters. This principle does not only hold for different firms, but also for different industries, sectors, and even countries.

Under perfect competition the initial allocation of allowances among the firms does not influence cost-efficiency of the market outcome (Montgomery, 1972). However, this result changes in the presence of market power. In the next section we will discuss possible distortions that may arise due to market power. In such cases the efficiency principle of equal marginal abatement costs may be violated.

A system of tradable emission allowance may also have repercussions on the output markets in which polluting firms are operating to sell their final output goods. An important question is what happens to the output price if the emission cap is reduced. To answer this question, it is important to note that a firm has, in

3.2 The economic efficiency of emissions trading

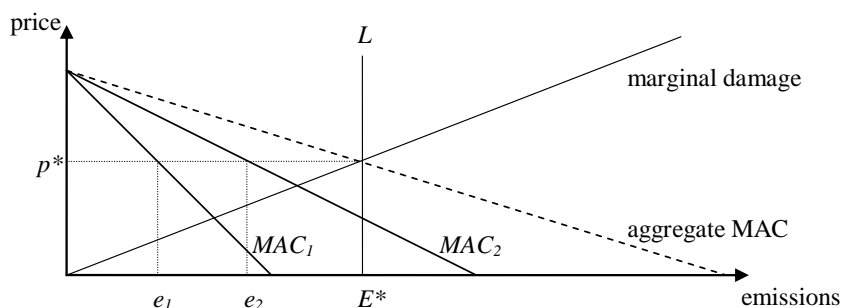


Figure 3.1: Economic efficiency of emission allowance trading

principle, at least two options for reducing emissions. First, it can try to reduce emissions per unit of output while holding output constant. This will normally increase the firms' unit costs, possibly making them prohibitively high, and thus spill over to consumer prices. The second option is to reduce output while holding emissions per unit of output constant. Lower output also translates into higher consumer prices, since the output good becomes scarcer. In general, the optimal strategy for each polluter is a combination of both, i.e. reducing output and reducing emissions per unit of output. Although technological progress helps to mitigate output contraction, the output price will rise more steeply, when the emission target becomes more ambitious.

Under a system of tradable allowances the question arises whether the price for emission allowances will be passed on to the consumer price and whether and to what extent it should be passed on. The answer is a definite "yes". Perhaps surprisingly, this answer is independent of the allocation scheme. Under both free and costly allocation of allowances, the emission allowance price must and will be passed on to the consumer price. To see this more clearly, let us think of a simple case where emissions are strictly proportional to the level of output, and where there is no further abatement technology. This is approximately true for CO₂ emissions resulting from combustion processes. Figure 3.2 illustrates this situation. Since emissions are strictly determined by output, total emissions and total output can be measured in the same units. In the figure E^c denotes the unregulated emission level under business as usual policy, while E' denotes the

3.2 The economic efficiency of emissions trading

emission target, which is lower than E^c . To achieve the lower emission target and hence output level, the price must increase from p^c to p' . For this purpose, the regulator has to issue a total quantity of emission allowances equal to E' . If these allowances are auctioned off, the allowance price must be equal to q . The total cost of buying allowances is represented by the area A . If the allowances are allocated to the firms for free, the firms also have to increase the market price from p^c to p' . The reason is twofold. From the perspective of a single firm, each firm has an opportunity cost of selling an allowance because this means less output and thus less profit. So a firm will only be willing to sell an allowance at a particular price. This opportunity cost, however, must be reflected by the market price for the output good. The second reason is that if the firms did not increase the market price or were not allowed to pass on the opportunity cost of selling allowances to the consumer price, this would result in market disequilibrium. Given the total amount of allowances E' , any price lower than the market clearing price p' would mean that demand would exceed supply and thus some consumers would have to be rationed. In the case of free allowances, firms enjoy so-called "windfall" profits, which are also represented by the area A . In Europe, the existence of windfall profits has been heavily criticized by politicians who had previously participated in designing the European allowance trading scheme with free allocation. Even the German competition authority claimed that passing on the market prices of allowances to the output price is illegal if emission allowances are allocated for free (Section 3.7.1.1 provides a detailed description of this case). We have shown that this is economically not feasible without accepting a disequilibrium situation.

It should further be mentioned that the degree of pass-through of allowance prices to output prices depends heavily on the market structure, in particular on the degree of the firms' market power in the output market. In the case of CO₂ emission trading schemes, the impact of allowance prices on electricity pricing is of particular interest. Electricity markets are often characterized by a more or less high degree of market concentration, where one or several firms are able to exercise market power. This particular market setting has been studied both from theoretical and empirical perspectives and the results are highly controversial (see Gullì, 2008, for an overview). Depending on the modeling framework and

3.3 Market power on the allowance market under free allocation

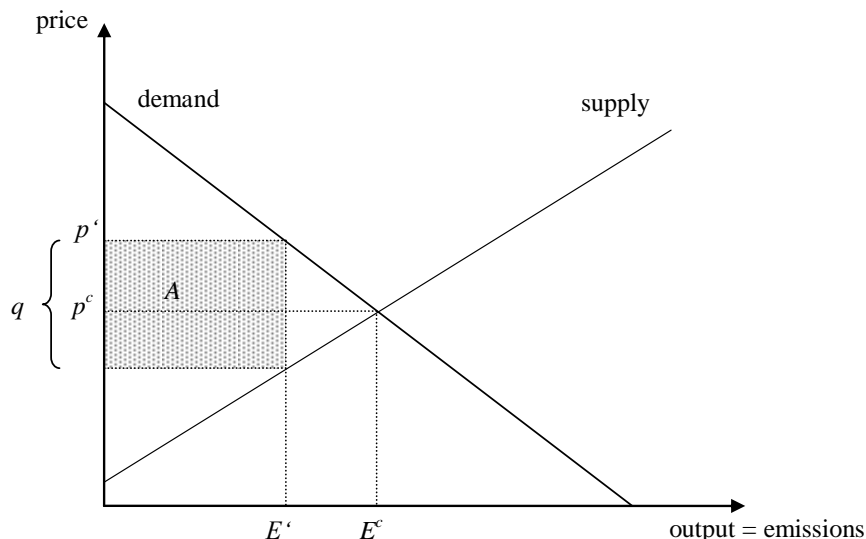


Figure 3.2: Cost pass-through of allowance prices under free and costly allocation

the assumptions concerning the demand function and price elasticity, the pass-through of allowance prices to electricity prices may be below or above the level expected in a competitive market. In his own analysis, Gullì (2008) finds that in the short term, allowance cost pass-through also significantly depends on the structural features of the electricity markets, i.e. on the power-plant mix, the available capacity in the market (whether there is excess capacity or not), and the price of CO₂ allowances (whether it is above or below the level making fuel-switching from coal to gas profitable). In the next sections, we will describe the circumstances under which market power may arise on emission allowance markets. We will also highlight the consequences of market power abuse for allowance and output prices, emissions, and social welfare.

3.3 Market power on the allowance market under free allocation

As in any other market, large firms are able to exercise market power also in allowance markets. This means that some firms do not consider the market price

3.3 Market power on the allowance market under free allocation

for allowances as given but try to manipulate the price via potentially large-scale purchases and sales. The firms' motivation to try influencing allowance prices can be twofold: Large net buyers want to reduce the financial burden arising from the emission constraint and large net sellers want to keep the price high so as to earn high revenues from selling. In both cases, the possibility of exerting market power depends on the ability of firms to influence prices on the allowance market, either unilaterally or collectively. To do so, these firms (price-setters) must represent a large share of total allowance demand over and against their competitors (price-takers).

If a dominant firm is a net seller of allowances, it will exercise monopoly power by selling less and abating less than is socially optimal. This situation is illustrated in Figure 3.3, where marginal abatement costs of one large firm (M) and a group of competitive fringe firms (interpreted as a single firm F) are represented by the curves MAC_M and MAC_F , respectively. Assume that M receives an initial free allocation of allowances I_M . Under perfect competition, the allowance market is in equilibrium when marginal abatement costs are equalized, leading to allowance price p_c . Accordingly, in a competitive allowance market, $(I_M - E_M^*)$ is the amount of excess allowances that firm M would sell to the fringe firms F at price p_c and the dashed rectangle represents the revenues M would earn from its allowance sales. Under market power, however, M has an incentive to hold back some allowances so that the price rises to p_m . It sells fewer allowances $(I_M - E_M)$ to the fringe firms F than under perfect competition and thus has to incur lower abatement costs since it keeps more allowances for its own use, i.e. $(E_M - E_M^*)$. The allowance revenues at price p_m plus the avoided abatement costs are then represented by the two shaded areas. While the dominant firm has lower net costs than in the absence of market power, the industry as a whole incurs a higher cost than under (perfect) competition and the allowance price is higher than optimal.

3.3 Market power on the allowance market under free allocation

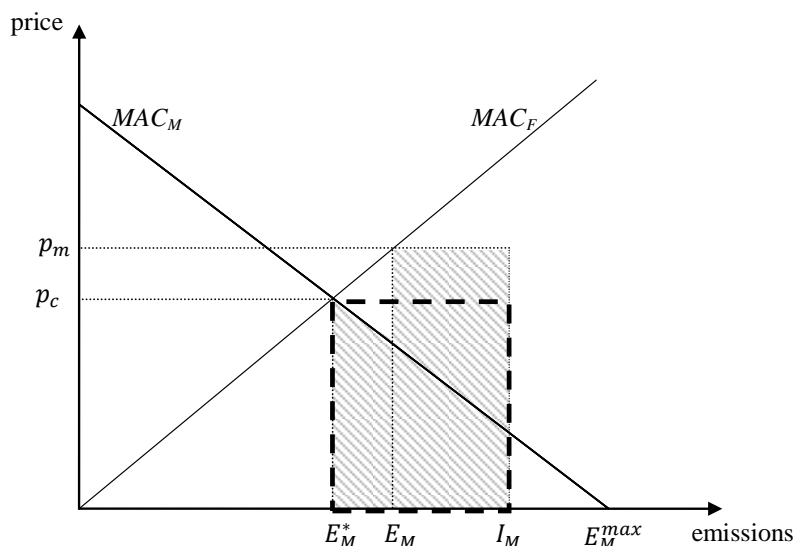


Figure 3.3: Market power when the large firm is a net seller of allowances

Conversely, if a dominant firm is a net buyer of allowances, it will exercise monopsony power by buying less and abating more than is socially optimal. This situation is illustrated in Figure 3.4, where the market price for emission allowances under perfect competition is again given by p_c . Assume again that M receives an initial free allocation of allowances I_M , which is now below its optimal level of emissions E_M^* . Under perfect competition, M would buy $(E_M^* - I_M)$ additional allowances at price p_c , leading to costs equal to the dashed rectangle. Under monopsony power, M demands fewer allowances than is socially optimal so that the price goes down to p_m . It will therefore emit less (E_M) and abate more ($E_M^* - E_M$) than under perfect competition and the expenditure for additional allowance purchases and emission abatement is then represented by the two shaded areas. Again, the dominant firm incurs lower net costs than in the absence of market power, but the total costs for the industry as a whole is higher than in the social optimum.

3.3 Market power on the allowance market under free allocation

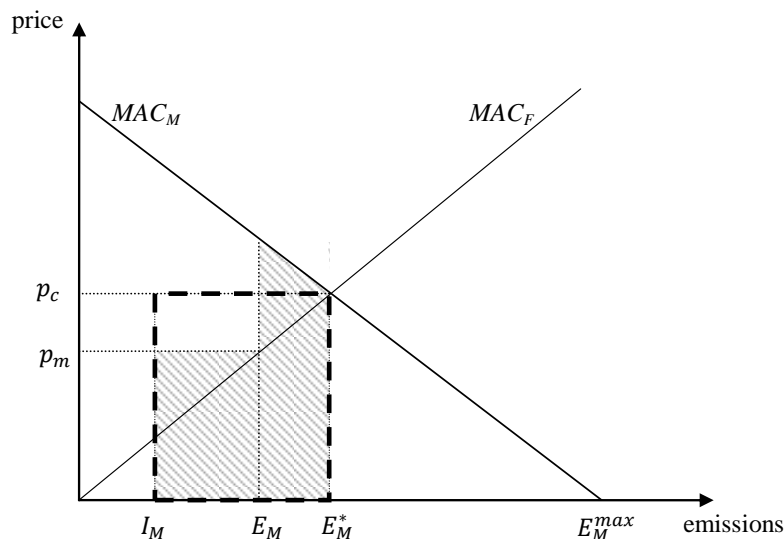


Figure 3.4: Market power when the large firm is a net buyer of allowances

Hahn (1984) was the first to advance a theory highlighting the possibility of market power in allowance markets. He considers a stylized model with one large polluting firm and a competitive fringe of many small polluting firms taking the allowance price as given. Hahn shows that market power vanishes if the dominant firm receives exactly the "efficient" amount of allowances, i.e. the amount that minimizes its total cost. In this case, the dominant firm has no incentive at all to participate in allowance trading and to exploit its dominant position. Hence, allowances are traded only among the competitive fringe firms, resulting in a socially efficient market outcome. The potential gain from a reduced allowance price is lower, the higher is the marginal abatement cost. So the extent to which firms use their market power also depends on the characteristics of their marginal abatement cost curves. Moreover, the elasticity of allowance demand from the price-taking competitors also influences the strategic behavior of large firms. If allowance demand from price-takers is elastic, a reduced price will increase their demand for allowances. As a result, the firms operating strategically have both to increase their abatement efforts and to accept lower profits. Conversely, if allowance demand from price-takers is inelastic, firms acting strategically will

3.3 Market power on the allowance market under free allocation

have greater influence on the allowance price, their abatement activity will be lower, and their profits will be higher. Requate (2006) and more recently Malueg & Yates (2009) show that the results of the Hahn model are much more general. They also hold true if there are several large firms forming an oligopoly vis-à-vis the competitive fringe firms.

What practical relevance does the problem of exercising market power actually have, and what are the potential policy consequences? First of all, optimal allocation of emission allowances to large firms is almost impossible in practice, since this would require the regulatory authority to have complete information about the emitters' marginal abatement costs. Should large buyers or sellers therefore be excluded from trade? The answer is a definite "no", since some trade is always better than no trade. One recommendation could be, however, to not obviously over-allocate (under-allocate) allowances to large firms if it is clear that they will sell (buy) allowances. Such case-by-case allocation is however hardly feasible as it is likely to violate the principle of competitive neutrality.

The second question centers on the allowance markets in which firms are likely to be sufficiently large to exercise market power. Here it is important to distinguish market shares in output markets from the percentage of trade volumes on the allowance market. In some sectors, notably utilities, firms may have a large market share in the output market, while their share of allowances in the allowance market is relatively small. This is usually the case for large allowance markets such as the U.S.-SO₂ market and the EU-ETS where firms from different sectors trade emission allowances. In most anti-trust legislations, the market-share threshold for which a conjecture about abuse of market power can be raised is at least 20 percent. In both the U.S.-SO₂ market and the EU-ETS, the trade volumes of even the largest buyers and sellers are well below this level. The problem of market power may arise, however, in small markets for specific pollutants.

3.4 Market power on the allowance market under auctioning

If allowances are auctioned off by the regulator instead of being distributed for free, the situation is not much different. There are no large sellers, but there may be large buyers. Following the Hahn model, the distortion is the larger, the greater is the deviation of the initial allocation from the final allocation. According to this argument, auctioning off allowances can in principle exacerbate the distortion arising from monopsony power. Indeed, price manipulation may occur if the auction mechanism is not properly designed. For instance, in a sealed-bid, uniform-price auction, each bidding firm submits a demand schedule specifying the number of allowances it is willing to buy at any given price. This mechanism creates incentives for large firms to strategically shade their bids in order to reduce the allowance price. Alternatively, a large firm could stop participating in the auction at all and limit itself to buying allowances on the resale market after the auction. In both cases, large firms may demand fewer allowances than they would under competitive market conditions.

There are several measures for mitigating the potential influence of large players in allowance auctions. One possibility is to establish a total limit for the amount of allowances that entities may purchase in a single auction. For example, the trading rules of the Regional Greenhouse Gas Initiative (RGGI) in the United States limit the number of allowances that may be purchased in any single auction to 25 percent of all allowances for sale in that auction. Economists, however, are skeptical about limitations of this kind as they might also impede economically useful allocations. Moreover, if auctions are open to entities without compliance obligations such as traders, brokers, or NGO's, this will enhance competition and limit opportunities for price manipulation.

Another potential way of handling the problem of bid-shading while retaining the relative simplicity of the uniform-price auction in comparison with other possible auction mechanisms (e.g. discriminatory-price auctions) is to allow for rebates or paybacks of auction revenues to the firms. Montero (2008) proposes such a mechanism that incentivizes firms to bid truthfully, i.e. according to their true demand, regardless of their size. With this mechanism, auction revenues are

returned to the firms in such a way that each firm's final payment is equal to the externality it imposes on the other firms. As a result, truthful bidding is a dominant strategy (i.e. it generates the highest utility for the bidder, irrespective of the behavior of the others), and therefore the auction result becomes cost-efficient.

It is fair to say that there is no clear picture as yet on the question of whether auctioning off allowances actually increases the likelihood of price manipulation. Montero (2009) conjectures that an allowance-auctioning system is less likely to induce the exercise of market power than free allocation. This view may be challenged for the following reason: Under free allocation it is not clear a priori who is a seller and who is a buyer. Even if firms are large, the volume of trade may be low (since the firms' initial allocation may be close to their optimal demand). Thus some large firms may not engage in much trading, while other large buyers and sellers may neutralize each other with respect to market power effects. Under a system of auctioned allowances, by contrast, it is clear from the outset that large firms will demand a large amount of allowances. This may not only provide incentives for bid shading but also induce collusion among the large bidders (see Section 3.5). Nor is there as yet any clear and obvious empirical evidence of major price manipulations by large traders on allowance markets. Moreover, there is no practical experience with the recent proposal by Montero (2008) about rebates of allowance auction revenues.

3.5 Cartel agreements

Besides the usual distortions through oligopolistic market power, which are not illegal per se, large sellers or buyers could in principle also form a cartel vis-à-vis small firms and agree to hold down the supply of allowances or jointly shade their bids in order to reduce the allowance price. Besides being illegal, such behavior is less likely in a allowance market than in a conventional goods market. The reason is that, for instance, there is no clear borderline in practice between large and fringe firms, so potential cartelists would be uncertain about how to ringfence their cartel. Moreover, large firms may be sellers and buyers, as reported by Rico (1995) in the case of the U.S. sulfur market. It is interesting to note that

3.6 Abusing allowance trading to manipulate output markets

the above-mentioned mechanism proposed by Montero (2008) is also suitable for preventing bidding cartels on allowances auctions since that mechanism turns out to be immune against cartel formation.

3.6 Abusing allowance trading to manipulate output markets

Allowance markets have repercussions on the associated output markets. We have already argued in Section 3.2 that allowance prices are passed on to output prices independently of whether allowances are initially allocated to the firms free of charge or at cost. We have also argued that this is in principle a desirable outcome. In fact, it is even socially optimal for consumers to bear part of the burden of reducing emissions. However, at least in theory there are several ways of abusing allowance trading systems to create distortions on the output market. In particular, firms may try to use allowance trading (a) to impede competitors on the output market by raising their costs on the allowance market, (b) as a collusive device for the benefit of a whole cartel, and (c) to increase market concentration.

3.6.1 Impeding competitors and market foreclosure

The logic of impeding competitors is as follows: Assume that firm A has a relatively clean technology and would in principle be a seller (under free allocation) or a small buyer (under auctioning) of allowances. In addition, one or several of A 's competitors on the output market (say, firms B and C) have dirty technologies and thus a high demand for allowances. Instead of selling spare allowances or buying only a small amount, A may have an incentive to preempt the allowance market in order to increase the abatement cost for its competitors B and C . For this purpose, A may decide not to use all the allowances it holds, but rather to hoard some of them. This strategy aims at decreasing the rivals' output market share and may even force rivals to exit or prevent new firms from entering the market.

3.6 Abusing allowance trading to manipulate output markets

Misiolek & Elder (1989) were the first to highlight this strategic opportunity, finding that hoarding of allowances by a dominant firm prevents its competitors from pursuing their optimal production and abatement strategies. This results in an additional strategic effect because the dominant firm now has an incentive to sell even fewer (or buy even more) allowances than in the simple model by Hahn (1984) of pure market power on the allowance market. Misiolek and Elder note that, depending on the initial allowance allocation, the strategic effect can either worsen or improve the inefficiencies identified by Hahn.

Von der Fehr (1993) and Sartzetakis (1997) extend the argument by Misiolek and Elder by studying the effects of raising rivals' cost strategies in an oligopolistic setting. They find that such strategies are profitable and that profitability increases with the stringency of the regulation and the abatement cost level. They show, however, that the effect of raising rivals' cost strategies on economic welfare is ambiguous and depends on the technological efficiency of the dominant firm relative to its rivals. More precisely, if the dominant firm expands its market share at the expense of a less efficient rival, overall efficiency and thus welfare may increase despite the decrease in industry output.

3.6.2 Using allowance trading to collude on the output market

Making agreements between firms to raise prices and limit production is considered hard-core cartel conduct and forbidden by almost every country's anti-trust law (e.g. Section 1 of the Sherman Antitrust Act, Article 101 (former Art 81) of the European Treaty). However, a group of firms could tacitly form a cartel by letting one firm hoard allowances so that it limits the capacity of all other firms. This may lead to lower output, higher prices, and higher profits to the benefit of all participating firms. Such a strategy may not even be illegal *prima facie* since it is usually legal for firms to sell or buy inputs amongst themselves. However, if the cartel authority discovers such an abuse, it might be treated in a similar way as a merger case.¹ The California NO_x case described in Section 3.7.1.2 displays

¹A transfer of a considerable value of assets enabling one firm to control the production of another is considered a merger according to the European merger regulation and the national

some of the features of this type of conduct.

3.6.3 Increasing market concentration through allowance trading

The third possible kind of anti-competitive behavior is increasing market concentration through allowance trading. Instead of increasing rivals' cost by raising prices for allowances one or several dominant firms could buy up all the allowances owned by weak competitors. This may even happen on a voluntary basis if small firms have an initial endowment of allowances and find it more profitable to sell the allowances and leave the market. Such a transfer of allowances from small to large firms will obviously result in higher market concentration. Accordingly, the market structure could change from (more or less perfect) competition to oligopoly. If the number of firms in the market decreases, prices on the final goods market would be expected to rise. In analogy to the argument proposed by Sartzetakis (1997), this is not necessarily the case since less efficient firms are prone to sell to more efficient ones. Increasing market concentration through allowance trading is more likely under a allowance system with unlimited validity than under a system where new allowances are issued each year. Indeed, there is empirical evidence for such concentration processes. After the introduction of individual transferable quotas (ITQs) for fisheries in Iceland the fishery fleet shrank substantially, while at the same time economic efficiency of the Icelandic fishery was considerably improved (Arnason, 2005).

In conclusion, it is impossible to prevent strategic behavior on the allowance market altogether. However, an increasing number of market participants alleviate the potential inefficiencies arising from market power. In practice, crowding-out on the output market due to market power on the allowance market is limited for a number of reasons. First, dominant firms only benefit from such a strategy if their competitors on the allowance market are largely identical with their competitors on the output market. In most allowance markets for air pollution control, it is reasonable to assume that among all firms participating in allowance trading many of them operate in different output markets. Therefore, hoarding

laws of several OECD countries.

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of allowances would be associated with high costs and relatively small benefits for dominant firms, since such conduct would not only affect their direct competitors but also firms operating on other output markets. Moreover, the allowance price is certainly not the only factor determining the competitive position of a firm. Both strategic manipulation and market concentration through preemption are more likely to become a problem in smaller local allowance markets than in large markets. Therefore, market power may be a more important aspect of water-pollution than of air-pollution control. Finally, the implementation of appropriate market monitoring mechanisms and information sharing between the regulation authorities involved may help in detecting attempts to manipulate allowance prices.

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There is only limited evidence that market power has caused concern in existing tradable emission allowance schemes. This is partly due to limited data availability. In order to formally test market power, one would need to estimate marginal abatement cost curves and compare these to actual allowance prices. A departure from the marginal cost-pricing rule would provide an indication of market power. To the best of our knowledge, studies of this kind are not available so far.

In the prominent examples of the United States SO₂ emission trading scheme and the European CO₂ emission trading scheme, market power has never been a serious issue. In both cases, allowance markets are characterized by a large number of participants and high trading volumes, thus reducing the potential price impact of one or a few dominant players. Accordingly, the risk of allowance market manipulations is larger, the fewer firms participate in the allowance system. It is therefore more likely to become in problem in localized allowance markets, such as markets for water pollution control. We will highlight this issue by referring to two cases, the Biological Oxygen Demand (BOD) allowance trading at the Fox river in Wisconsin, United States, and the Hunter River Salinity Trading Scheme (HRSTS) in New South Wales, Australia. In the following sections,

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we will first consider emission markets where allowances are mainly allocated for free (EU-ETS, Reclaim, Fox river BOD trading) and then extend our analysis to auctioned allowance markets (RGGI and HRSTS).

3.7.1 Special observations on grandfathered allowance markets

Though there has been no clear-cut evidence of allowance market manipulation in the context of the European emission trading scheme, there are two issues worth noting. The first concerns the relationship between the emission allowance market and the imperfectly competitive electric power industry. This relationship was at the core of a debate during the first trading period from 2005 to 2007, in which the ability of electric utilities to pass through the cost of CO₂ allowances to wholesale prices was criticized. Since emission allowances were allocated for free, some firms were able to reap additional, so-called windfall profits. As was set out in Section 3.2, this criticism ignores the fact that cost pass-through is a desired effect from an efficiency point of view, independently of whether firms pay for the allowances or receive them for free. Accordingly, one controversial issue was posed by the decision on the part of the German competition authority to impose a 25 percent limit on the pass-through of emission allowances to electricity prices (see Section 3.7.1.1).

It is very important to understand that the pass-through of allowance costs is not an indicator of market power on the allowance market. Perhaps surprisingly, it can in fact be quite the opposite, as the degree of pass-through from allowance to output prices is likely to be higher under competition than under market power. The intuition for this phenomenon is as follows. Under perfect competition, a firm's marginal cost of production is close to the market price. If additional costs are added to marginal production cost, the firm will either reduce its output (in case of strong competition from foreign competitors that are not subject to emissions trading), or firms will pass through the additional cost of emission allowances to the consumers. A firm exercising market power, by contrast, sets its price at that point of the demand function where consumers' demand starts to get elastic. Since a further increase of the price will therefore cause too much

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demand reduction, a firm with market power does not find it profitable to pass through its additional cost fully to consumers. This effect is a typical effect, though not a general rule. Under certain demand and technology conditions, imperfect competition on electricity markets may also enable power companies to enforce a higher pass-through rate compared to competitive markets (see Gullì, 2010, for a theoretical analysis). In fact, Gullì (2008) summarizes a number of empirical studies showing that the pass-through rates of EU allowance prices to electricity prices vary significantly between countries and periods and may range from zero to more than 100 percent.

Figure 3.5 illustrates why the pass-through of allowance prices to final output prices under perfect competition is usually lower than under imperfect competition (monopoly). For this purpose, constant marginal costs (MC) and linear demand are assumed. Under perfect competition firms make no profit and (in a closed economy) have to fully pass-through the allowance price (p^a) to the consumers. The monopolist, by contrast, sets his price (p^m) at the point where the marginal revenue curve intersects the marginal cost curve. If there is a price for emission allowances, he will pass on less than 100 percent of the allowance price to consumers because otherwise he would incur reduced profits. Note that under increasing marginal cost, pass-through will be less than 100 percent, even when the emission market is perfectly competitive.

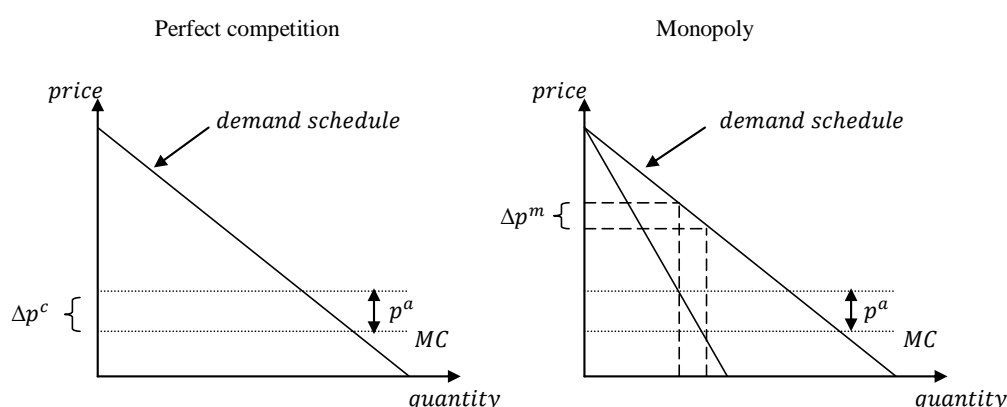


Figure 3.5: Allowance price pass-through in competitive markets and under monopoly. Perfect competition: $\Delta p^c = p^a$. Monopoly: $\Delta p^m = \frac{1}{2}p^a$.

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Besides the debate on the allowance price pass-through, another issue that has raised some questions concerning the potential for market power in the European emission market relates to the development of European allowance prices after May 2006. At that time, the significant over-allocation of emission allowances during the first trading period was revealed, leading to a sharp drop in the allowance price. However, the allowance price did not immediately fall to zero as might have been expected, given that there was an evident over-supply of allowances in the first trading period and banking of allowances for the second period was not permitted. Instead, the allowance price on the spot exchanges remained significantly positive during the year 2006, eventually converging to zero in the second half of 2007. This poses a number of questions concerning the factors that determined the allowance price during this period and why the price did not fall to zero immediately. One suggested answer might be that it was in the interests of some powerful players such as energy utilities to keep the price positive, for instance to justify higher electricity prices. This kind of allegations, however, have never been proven.

In fact, the strongest empirical evidence with regard to market power on emission allowance markets comes from the Reclaim market in California, where electric power facilities seem to have used the NO_x allowance trading system to exercise market power in the California electricity market. Several studies conclude that some power utilities, which were able to exercise market power on the California electricity market, paid significantly higher NO_x prices than their competitors in order to cost-justify higher electricity prices (see Section 3.7.1.2 for details). Since many of the features are very specific to the Californian context, this problem cannot be generalized to all allowance trading schemes. Nevertheless, the experience in California certainly highlights the importance of transparent and liquid allowance markets in preventing anti-competitive behavior.

Concerns over strategic manipulations are also common in localized allowance markets with a small number of participants. One such example is the allowance trading system established for discharges of biological oxygen demanding wastes (BOD) into the lower Fox river in Wisconsin. The Fox River Program was established in 1981 and covers five pulp and paper mills and two municipal wastewater treatment plants, located on each of the three segments of the river. Although an

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analysis previous to the implementation of the scheme had predicted significant potential gains from allowance trading (of annually seven million U.S. dollar), the actual trading activity has been negligible. According to Nishizawa (2003), only two trades took place from the establishment of the scheme in 1981 until 2003. Von der Fehr (1993) conjectures that this may be the case because firms within the same industry do not want to sell allowances to buyers with whom they compete in the output market. However, such strategic considerations are probably not the most important reason to explain this outcome. As stated in a report by the Environmental Protection Agency (EPA, 2001), there are other reasons for the limited trading activity. First, the BOD Program establishes severe restrictions on the ability of sources to trade allowances. Trading is allowed only if the buyer is a new facility, is increasing production, or is unable to meet the required discharge limits despite optimal operation of its treatment facilities. Second, there is uncertainty about the legal viability of the allowances being traded, since the Clean Water Act does not explicitly allow trading. And finally, the relevant facilities developed a variety of compliance alternatives that were not contemplated when the regulations were drafted.

3.7.1.1 The prohibition of CO₂ allowance price pass-through by the German competition authority

In the year 2005, following complaints by several companies from electricity-intensive industrial sectors concerning the cost pass-through of CO₂ allowances to electricity prices, the German competition authority (*Bundeskartellamt*) opened an investigation of potentially abusive electricity price increases by the German energy utilities RWE and EON. Together, RWE and EON had a dominant position on the German electricity market at that time, both in terms of the production and the distribution of electricity. Accordingly, the German competition authority had to analyze whether the electricity price increase due to the pass-through of allowance costs significantly deviated from what would have occurred in a competitive market.

In their initial assessment of the case, the *Bundeskartellamt* principally supported the view that even if allowances are allocated for free, they still represent

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an opportunity cost and should therefore be included in the firms' cost calculations. However, the competition authority presented two major arguments against (full) allowance cost pass-through to electricity prices. First, the authority stressed that the competitive conditions in other sectors participating in emissions trading (in particular mineral oil, steel, cement, paper) did not allow the pass-through of allowance costs. Second, the authority claimed that the concept of opportunity cost holds only if the allowances are effectively available for sale but not if they are used for production. For the period under question, the competition authority asserted that only a relatively small amount of the allowances allocated to the utilities could have been used for other purposes than compliance such as sale on allowance exchanges. In fact, for the compliance period from 2005 to 2007, RWE was a net buyer of 13.6 million CO₂ allowances. Therefore, the *Bundeskartellamt* decided that only those allowances for which realistic opportunities for alternative uses existed could be factored into the electricity price. Accordingly, the *Bundeskartellamt* judged that there could be no objection to a pass-through of no more than 25 percent of the allowance value.

In its response to this ruling, RWE formally committed itself to selling a significant amount of electricity capacity to its industrial customers via several independent auctions (i.e. not via the conventional energy exchange in Leipzig, EEX), in which the price of freely allocated emission allowances would be set at zero.² The total amount of electricity to be auctioned off from 2008 to 2011 adds up to 46 million MWh, which roughly corresponds to the annual electricity sales of RWE to industrial customers in Germany. The *Bundeskartellamt* accepted the formal commitment proposed by RWE and subsequently closed the investigation. However, it turned out that the auction results were not much different from the electricity wholesale prices on the EEX because the auction participants had effectively considered the allowance prices when making their bids. Therefore, the formal obligation made by RWE has proven ineffective in terms of the outcome desired by the *Bundeskartellamt*.

²In fact, the starting price in the auctions was set to the full cost of an (amortized) hard coal or lignite utility minus the cost of the freely allocated emission allowances (*Bundeskartellamt*, 2007).

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From an economic point of view, however, the investigation by the *Bundeskartellamt* was mistaken in the first place. First, the cost pass-through of emission allowances in a competitive market should not be zero, as suggested by the *Bundeskartellamt*. As we have already argued, the pass-through rates in an imperfectly competitive setting may even be lower than under perfect competition. The lower pass-through rates in the industrial sectors mentioned by the competition authority can rather be attributed to other factors such as international competition from less closely regulated countries incurring lower carbon costs or none at all.³ Second, the concept of opportunity costs applies to all freely allocated emission allowances, independently of whether they are available for sale on the allowance market or used for production. If firms are not allowed to factor the allowance costs into their pricing decisions, this will lead to market disequilibrium, as the discussion in Section 3.2 has demonstrated.

3.7.1.2 The NO_x allowance price bubble in California's Reclaim market

While in the context of the EU-ETS alleged allowance price manipulations due to market power could never formally be proven, the developments in the California Reclaim market have given rise to more convincing evidence of allowance price manipulations. In California, after several years of relatively low allowance prices due to overly generous initial allowance allocations, the prices for NO_x allowances under the Reclaim program increased sharply during 2000 and 2001, while at the same time some facilities had difficulty in achieving their emission targets.

According to Kolstad & Wolak (2008), several factors contributed to this development. First, the demand for electric power increased heavily in 2000 and 2001, greatly exceeding the available supply. As alternative power sources, such as hydro power, did not materialize due to adverse weather conditions, the increased demand had to be met by production from older, less efficient power plants. Second, due to the relatively low NO_x allowance prices during the first years of the program, the affected facilities had invested little in pollution control

³Chapter 4 provides a full discussion of competitiveness issues in the context of emissions trading.

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technologies. During the year 2000 the allowance market reached the "cross-over point", implying that there were no longer excess allowances available for purchase. At this point the lack of (installed) abatement technology became apparent and further contributed to the allowance price increase. Finally, the dramatic increase in NO_x allowance prices coincided with a substantial increase in the amount of market power exercised in the California electricity market (Borenstein *et al.*, 2002; Joskow & Kahn, 2002; Wolak, 2003).

Based on these observations, Kolstad & Wolak (2008) analyze the interactions between the NO_x allowance market and the California electricity market. The authors present evidence that some electric power facilities paid significantly higher NO_x prices than other allowance market participants while at the same time holding a larger share of unused allowances during 2000 and 2001 compared to previous years. Kolstad & Wolak (2008) conjecture that the inflated NO_x prices were then used to cost-justify higher bids in the day-ahead and real-time California electricity markets.

To appreciate this argument properly, some specific features of the electricity market in California during that period need to be explained. First, the power generation facilities showed a considerable disparity in NO_x emission rates, implying that increases in the allowance price could have changed the least cost dispatch of the generation units. Electricity suppliers operating facilities with different NO_x emission rates may thus have benefited from an increase in the price of NO_x allowances since it enabled them to obtain additional profits from generation units with lower NO_x emission rates. Second, the California electricity market covers a geographically larger area than the Reclaim market. Accordingly, electricity suppliers with generation facilities both in and outside the Reclaim market may have had an incentive to increase the price of NO_x allowances in order to place higher bids for all the electricity they produce.

It should be emphasized that many of the above observations are quite unique to the Californian context in the specific period under study. For instance, the fact that there was no uniform market price for NO_x allowances facilitated the use of allowances to raise electricity prices. Due to the bilateral nature of allowance transactions, electricity suppliers interested in raising allowance prices

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could do so without affecting the prices paid by other buyers. Under a transparent market-clearing mechanism, such behavior would have been less likely. Therefore, the allowance price manipulation evidenced in the Reclaim market is not related to the "raising rivals' costs" strategy discussed before. In the Reclaim market electricity suppliers rather tried to charge prices close to the monopoly price, which violates the prohibition of abusing a dominant position in line with Section 2 of the Sherman Antitrust Act. By generating high allowance prices they were able to prove high costs and thus camouflage monopoly prices as high-cost competitive prices. Since several firms participated in this kind of conduct, a tacit agreement on concerted action cannot be ruled out.

3.7.2 Special observations on auctioned allowance markets

So far, there is little practical experience with emission markets where all allowances are sold through auctions. At present, such markets include the RGGI market and the Hunter River Salinity Trading Scheme. Under the RGGI, no evidence of anti-competitive conduct was detected for the auction process, barriers to participation in the auctions, or the auction results in the first six allowance auctions in 2009 (Potomac Economics, 2010). Although allowance prices both in the RGGI auctions and on the secondary market decreased considerably during the first year of operation, this is rather attributable to changes in expectations regarding the future use of allowances than to anti-competitive behavior. This result is reinforced by the strong participation of firms in the allowance auctions (at least 46 bidders participated in each auction) and growing trading activity on the secondary market.

Similarly, there has been no apparent collusion or anti-competitive behavior in the biannual auctions held under the Hunter River Salinity Trading Scheme since 2004. In all auctions, the total amount of 200 allowances were distributed between eight to 11 companies. Moreover, average allowance prices increased from 507 Australian dollar in 2004 to 947 Australian dollar in 2008 (DEC, 2004; NSW Government, 2010).

From the empirical evidence on market power in emission markets we can draw two main conclusions. First, if allowance markets are sufficiently large, price manipulation and other abuses of market power are less likely to happen. This observation, however, does not rule out the use of tradable emission allowances on a local and regional level, where the number of firms is typically small. For example, the Hunter River Salinity Trading Scheme seems to work well despite a relatively small number of participants. The Fox River Trading Program has proven disappointing in terms of the actual trading activity, but the small volume of trade can be explained by shortcomings in the system's design and restrictive trading rules rather than by potential strategic behavior of the participants. The second conclusion addresses the importance of transparency in allowance markets, in particular the uniformity of allowance prices across all market participants. If allowances are traded periodically using a market-clearing price mechanism and ensuring anonymity for buyers and sellers, allowance price manipulations such as those observed under the Reclaim program are less likely to occur.

3.8 Concluding remarks

In this chapter we have given an overview of possible competitive distortions created by emission trading systems. Two main types of distortions have been identified, those arising from the exercise of market power on the allowance market and those due to the (ab)use of the allowance trading system to improve the competitive position on the output market.

Under a system of free allowance allocation, large allowance sellers have an incentive to use more allowances for compliance than is efficient to keep the allowance prices high and make profits from selling allowances. This is the usual monopoly/oligopoly effect. In addition, under both free and auctioned allowance systems, large buyers have an incentive to shade their demand to keep prices low. This type of conduct creates differences in the marginal abatement costs across firms and thus leads to a deviation from the least-cost solution. This kind of conduct vanishes, however, if the number of participants is sufficiently large. For large existing allowance markets, notably the U.S. sulfur and the European CO₂ market, it has not been a severe problem so far. It might become a problem

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if auctioning were introduced and large buyers started shading their demand. Moreover, illegal agreements and the formation of large seller or buyer cartels can never be ruled out. Whether the impact of such concerted action is more severe under free allocation of allowances or under auctioning is an open question and crucially depends on how allowance auctions will be designed.

Allowance markets can also be abused to influence the output market. In this context, following a raising rivals' cost strategy is especially profitable for a firm that has a lower emission coefficient than its competitors and hence a lower demand for allowances. In the extreme case, (some) competitors will leave the market. In addition, under free allocation, firms may jointly decommission a certain share of the allowances in order to increase their rent. Finally, firms with market power may want to increase allowance prices to disguise monopoly prices as high-cost competitive prices. All these practices are less likely to be profitable, and thus less likely to occur, if the number of participants is large and the industries participating in allowance trading are heterogeneous.

It is important to emphasize that setting up a system of tradable allowances with a binding cap always feeds back to the output market. Depending on market structure, elasticity of demand and supply, and marginal abatement cost curves, allowance prices will pass through to consumer prices. This is in itself socially desirable and cannot be considered an abuse per se, except in special cases. This feedback, however, typically also results in a lower number of firms and higher market concentration, thereby increasing the risk of market power.

The bottom line is that if allowance markets are large and encompass firms from different sectors, if the trading procedure is transparent, and if there is a unique price, the risk arising from market power and its potential abuse is low. This does not, however, mean that smaller allowance markets should not be established. Smaller allowance markets can be very effective for local pollutants if compliance with strict thresholds is ecologically advisable. Since a single trader in a small market has potentially more influence to manipulate prices than in a large market, competition commissions and anti-trust authorities should keep an eye on smaller allowance markets with respect to strategic abuse, but also observe auctions with large buyers to avoid concerted action. So far, anti-trust enforcement on allowance markets has been very limited. In part, this can be

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attributed to the slow development of emission markets caused by the fact that initial allowance allocations are generally large such that the emission constraints only become binding after some time has elapsed.

Moreover, there is hardly any research so far on anti-competitive effects in other allowance trading systems different from cap and trade. It is to be expected that similar effects to those described above can arise on green and white certificate markets. With respect to baseline-and-credit schemes there is less risk of abusing the system to exercise market power. The reason is that the scope of such markets is still too small compared to cap-and-trade markets. Baseline-and-credit schemes may be abused, however, by firms trying to manipulate the baseline of projected emissions in order to gain a competitive advantage.

Finally, it should be emphasized that although anti-competitive effects can arise on and through allowance markets, the resulting distortions should not be over-stated. Efficiency gains from trading compared to command-and-control regulation are likely to dominate possible efficiency losses through anti-competitive effects on allowance markets. A comparison of tradable allowances systems with emission taxes is more difficult. An emission tax system is less likely to be abused for anti-competitive behavior unless firms lobby for exemptions. However, a full comparison between emission allowances and emission taxes must consider many other criteria and is beyond the scope of this chapter.

Chapter 4

Emission allowance trading and competitiveness

4.1 Introduction

The potential impact of emission allowance trading on the competitiveness of firms, industries, or even countries is a hotly debated issue. Particularly in the context of international climate policies, many countries are reluctant to impose unilateral emission limits because they fear a loss of competitiveness for their national industries on global output markets. In addition, the implementation of emissions trading may also raise competitiveness issues at the national level.

Competitiveness is a very broad term that can encompass a variety of aspects such as trade flows, terms of trade, carbon leakage, domestic employment, and production. It is common to define competitiveness in terms of a firm's ability to maintain or expand its market position based on its cost structure (cf. Reinaud, 2005). As a general rule, environmental policy instruments should be competition-neutral, meaning that they should have the same effect on all emitters in terms of equal marginal abatement costs. In principle, a system of tradable allowances fulfills this requirement since the same price holds for all emitters. In Chapter 3 cases have been described where market power on the allowance market may lead to distortions among firms. In the following, the focus lies on competitive distortions that may arise from uneven conditions (a) between firms, industries, and jurisdictions regulated under the same allowance trading

4.2 Factors affecting firm competitiveness under emission allowance trading

scheme, (b) between industries in one jurisdiction regulated under different policy instruments, and (c) at the international level between countries with different environmental regulations.

The remainder of this chapter is organized as follows. The next section will give a general overview of the factors affecting firm competitiveness under a system of tradable emission allowances. In Sections 4.3 and 4.4 we will then analyze the different classes of competitive distortions arising from emissions trading both within a system of tradable allowances and on the international level, i.e. between countries or regions that have implemented emissions trading and countries or regions that have not. In Section 4.4 we will investigate potential remedies for (international) competitive distortions arising from emissions trading. In Section 4.5 we will then review the empirical evidence on the impact of the European emissions trading scheme on firm competitiveness and describe the results of various simulation models analyzing the (potential) carbon leakage effects of different global emissions trading policy scenarios. Finally, Section 4.6 will summarize the main results of this chapter and provide some policy conclusions.

4.2 Factors affecting firm competitiveness under emission allowance trading

The competitiveness of firms may be adversely affected by emissions trading due to the additional costs they incur compared to their unregulated or less regulated competitors. As a result, the affected firms have to decide between two alternatives. Either they pass through these additional costs to their output prices at the expense of a loss in market share or they do not (fully) pass through the additional costs and accept a reduction in profits while maintaining their market shares. Ultimately, the costs of emission regulation may be so large that it becomes profitable for firms to shift their production to other regions or countries with weaker regulations.

Figure 4.1 illustrates the main factors determining the impact of an emissions trading scheme on firm competitiveness. The first and most important factor is the energy intensity of the firms' production, which can be broken down into two

4.2 Factors affecting firm competitiveness under emission allowance trading

aspects. On the one hand, firms or industries with higher energy intensity have to purchase more emission allowances, directly increasing their production costs. On the other hand, energy-intensive firms or industries face an indirect cost increase because electricity prices are likely to increase as a result of emissions trading. The indirect effect through rising electricity prices also affects firms that do not participate in emissions trading. Accordingly, energy intensity has a negative effect on competitiveness.

The second factor to affect firm competitiveness is the ability to pass through higher costs to output prices. If firms or industries operate in a context with relatively low demand elasticity and little competitive pressure, they are in a better position to pass through allowance costs and thus their competitiveness is less seriously affected. Conversely, firms or industries competing in global output markets generally face a higher risk of losing competitiveness because they cannot pass through allowance costs without losing market shares to international competitors that do not incur these additional costs.

As illustrated in Figure 4.1 competitiveness is also influenced by the ability of firms or industries to abate emissions or to substitute emission-intensive inputs. Competitiveness is less seriously affected if a firm can easily and inexpensively implement abatement measures or switch to less emission-intensive inputs. Finally, the fourth factor to impact on competitiveness is the incentive created by the emissions constraint to invest in innovative low-carbon technologies. If innovations in low-carbon technologies succeed in penetrating the market, this may lead to a positive effect on competitiveness, particularly in the long run.

The overall effect of emissions trading on competitiveness depends on the relative strength of these different factors. In particular, while the effects associated with energy intensity, cost pass-through, and abatement opportunities will certainly affect competitiveness in the short run, a positive long-run effect on competitiveness from low-emission technological innovations is less certain. The latter effect depends both on the incentives provided by the emission trading scheme to develop innovative technologies and on the direction taken by international climate policy in the future.

4.3 Competitiveness effects within a system of tradable allowances

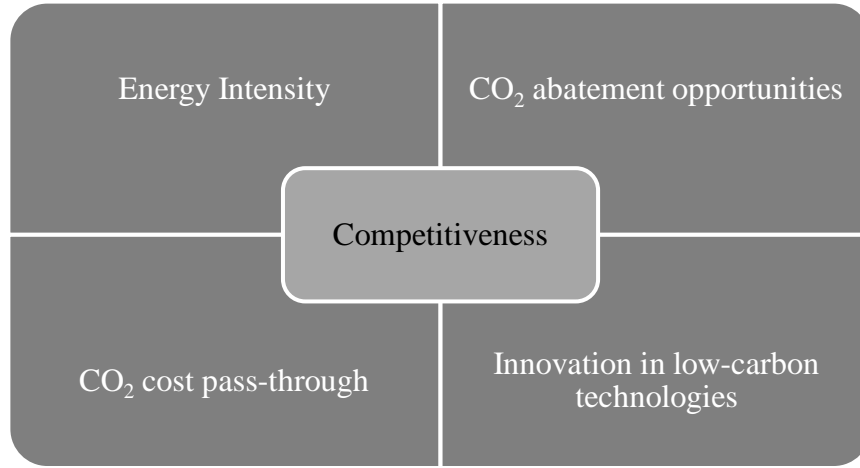


Figure 4.1: Impact of emissions trading schemes on competitiveness

4.3 Competitiveness effects within a system of tradable allowances

Within a system of tradable emission allowances, competitive distortions may result from sector- or country-specific allowance allocation rules leading to different marginal abatement costs across participating companies, sectors, or countries. In reference to this issue, the Green Paper on emissions trading by the European Commission asserts that there is "a trade-off between providing greater equality of treatment and more simplicity, on the one hand, and Member States maintaining greater autonomy, on the other" (COM, 2000). Based on this argument, allowance allocation was not coordinated between the member states in the first two trading phases of the EU-ETS, leading to differential treatment of otherwise similar companies and sectors across the EU (Böhringer & Lange, 2005; Woerdman, 2001). For instance, while most member states distributed all the emission allowances for free, some states auctioned off a certain share of the allowances. Most member states distributed the free allowance allocations according to historical emissions, while other member states applied industry-specific benchmarks. Moreover, the member states implemented different exemption criteria and special allocation rules, different allowance reserves for new entrants, and different

4.3 Competitiveness effects within a system of tradable allowances

definitions of installation closure. These numerous exemptions and special allocation rules plus the lobbying efforts by the relevant industries to obtain the highest possible allowance allocations led to an over-generous initial allocation, particularly in the first trading phase.¹ As a result, even with free allocation of allowances, the so-called assignment factors (i.e. the ratio between the amount of emission allowances allocated and historical emissions) were quite different for firms from various European member states (Böhringer & Lange, 2005; van der Laan & Nentjes, 2001). Therefore, the European Union has decided to abolish the National Allocation Plans in favor of harmonized allocation rules from the third trading phase onward.

However, no satisfactory solution is feasible with any scheme allowing for free allocation of allowances, since competitive neutrality would require the assignment factors to be equal. Böhringer & Lange (2005) show that, given the Kyoto commitments for the different European countries, there is a trade-off between competitive neutrality and cost efficiency. Competitive neutrality is either not feasible if emission targets in the non-trading sectors are required to be efficient or it induces large inefficiencies in the abatement efforts in the non-trading sectors. Therefore, the simplest and most effective way to alleviate both cost-inefficiencies and competitive distortions between firms, sectors, and countries within an emissions trading scheme is by auctioning off a large share (or all) of the allowances.

On the other hand, the competitiveness of companies participating in emissions trading may be affected differently depending on whether the main competition they face is national or international. In industries producing mainly for the domestic market, companies are more likely to pass through the additional cost of emission restrictions to their product prices and are thus less adversely affected by emissions trading. Conversely, industries mainly selling their products on international markets have little opportunity to pass through the allowance costs if their international competitors face weaker emission limits or none at all. In the latter case, free allowance allocation may be seen as a suitable way of compensating firms for the additional costs they will necessarily incur. However,

¹One might argue that the European regulators were prepared to accept the loss of efficiency and competition neutrality to secure the support of the important industrial lobbying groups for an emissions trading scheme.

4.3 Competitiveness effects within a system of tradable allowances

as will be discussed in Section 4.5.3, free allowance allocation has its drawbacks in balancing out the competitive disadvantages of firms at an international level.

Another source of distortions arises from the fact that emissions trading systems usually cover only a part of the emitters in a certain country while the other emitters are regulated by alternative policies. For instance, the EU-ETS includes most industrial sectors, but not the transport sector or households. While this is partly due to difficulties in measuring and controlling emissions in the latter sectors, dividing the economy into an ETS and a non-ETS sector may lead to an unequal distribution of the reduction burden between these two sectors.² Indeed, several studies on the EU-ETS conclude that the lion's share of emission reductions is borne by sectors not participating in emissions trading, leading to substantially higher total costs than an emissions trading scheme embracing all CO₂-emitting sectors (Böhringer *et al.*, 2005; Peterson, 2006). The unequal treatment of ETS versus non-ETS sectors may also lead to competitive distortions if competing firms face different costs caused by environmental regulation. We have already argued that there is always an efficiency trade-off between equal treatment of ETS and non-ETS sectors, on the one hand, and competitive neutrality across member states, on the other.

Finally, in analyzing the effects on competitiveness it is important to consider both the direct and the indirect costs of emissions trading. As mentioned above, the direct costs comprise abatement efforts and allowance purchases (or equivalently the opportunity costs of holding allowances if they are allocated for free), whereas the indirect costs result from input price increases due to emission trading such as increases in energy prices. In the case of energy-intensive firms, the indirect costs often represent a much more onerous burden than the direct costs of emissions trading. So even if several regions or countries are regulated by the same emissions trading scheme, as this is the case in the European Union, different competitiveness effects may arise from different structures of the energy production industries. In European countries with a high share of nuclear or hydro power (France, Sweden, etc.), the impact of emissions trading on electricity prices can be expected to be much less substantial than in countries with a high

²In principle, a rather simple way around the measurement problem is to measure CO₂ emissions based on the emission intensity of fuel inputs.

4.4 Competitiveness effects at the international level

dependence on fossil fuel utilities, particularly on emission-intensive coal (Germany, United Kingdom, etc.).³ This may give rise to location advantages for the first-mentioned countries and lead to a relocation of energy-intensive industries to these countries. The shift to less emission-intensive energy sources is a desirable effect of any emissions regulation and does not lead to a deterioration of environmental quality. However, the evaluation of relocation decisions becomes more complicated when it is associated with a shift of production to countries with less stringent environmental standards, as we will discuss in the next section.

4.4 Competitiveness effects at the international level

At the international level competitive distortions may arise between countries with different environmental regulations. Emitters in countries with stricter environmental standards and hence higher marginal abatement and production costs may be disadvantaged compared to emitters in countries with less strict regulations or none at all. The potential effect is that certain industries will move their production to less tightly regulated countries, thus increasing emissions elsewhere. This effect is known as carbon leakage. In fact, this problem is not directly related to a specific policy instrument like tradable allowances but rather to the overall stringency of environmental regulation.

To protect the relevant industries from competitive disadvantages, many emissions trading schemes define special rules for industries facing the risk of carbon leakage. According to Dröge (2009), these rules can be divided into two broad categories: behind-the-border measures and border measures (also called border-carbon-adjustment measures). Behind-the-border measures include direct financial compensations and free allocation of allowances. Border-carbon-adjustment (BCA) measures comprise tariffs or taxes on imports, issuing tradable allowances

³If electricity could be traded freely between countries, it would be expected to observe a unique electricity price across Europe. But due to relatively high transportation cost (transmission losses) and transmission bottlenecks between countries, electricity prices still vary widely from one country to another.

4.4 Competitiveness effects at the international level

according to carbon content of imports, rebates for exports, or full border adjustment.

One popular behind-the-border measure is to exclude the relevant industries from allowance auctions and to distribute emission allowances for free instead. As discussed above, this is an imperfect measure for mitigating regulated firms' competitive disadvantage since these firms still face the emission costs in their marginal production decisions. Moreover, long-term free allocation has a subsidy effect and represents a major fiscal opportunity cost for governments (Stephenson & Upton, 2009).

BCA measures are alternative ways to account for the fact that goods from some countries are not subject to emission restrictions and therefore do not include the CO₂ content in their prices. One potential remedy is to levy a border carbon adjustment tax or tariff on imported goods reflecting the costs of CO₂ emissions implicitly contained in the product. Alternatively, importers could be required to purchase tradable allowances according to the carbon content of imported goods. Provisions for BCA instruments can be found in several climate policy bills proposed by the U.S. Senate (e.g. the Lieberman-Warner and the Bingaman-Specter bills).⁴

BCAs may differ from region to region according to the respective carbon intensity of production. Since carbon intensities vary substantially across regions, this gives import taxes an advantage over other adjustment policies. However, pricing imports according to their CO₂ content only corrects the cost disadvantages of domestic producers at home, but it does not alleviate competitive distortions abroad. To offset the latter effect, a country can also grant a border rebate for exports to under- or unregulated countries. Finally, combining BCAs for both imports and exports leads to full border adjustment, where only the emissions from domestic consumption are regulated. Such a full border adjustment policy is equivalent to the destination principle in value-added tax systems.

⁴The Lieberman/Warner Climate Security Act requires the emission content of imports from unregulated countries to be covered through the purchase of international allowances (<http://www.opencongress.org/bill/110-s3036/text>). Under the Bingaman/Specter Low Carbon Economy Act importers have to hold emission allowances when the emissions in the unregulated producing country exceed a baseline level (http://energy.senate.gov/public/_files/END07842_xml1.pdf).

4.4 Competitiveness effects at the international level

Yet another option to account for international competitive distortions is to grant rebates to all domestic production, independently of whether it is consumed at home or abroad. This mechanism eliminates the cost disadvantages of emission regulation, but unlike the full border adjustment policies it does not provide incentives to reduce the domestic consumption of emission-intensive products. Full production rebates for energy-intensive, trade-sensitive industries correspond essentially to an output-based allowance allocation with updating and thus entails numerous efficiency problems. Accordingly, a full domestic rebate would be an inferior option compared to border carbon adjustments. Moreover, it should be noted that policies combating leakage do not necessarily reduce global emissions (Fischer & Fox, 2009). The reason is that all adjustment policies either increase the cost of foreign production or decrease the cost of domestic production. As a result, domestic production (and with it domestic emissions) increases compared to a situation without adjustment while at the same time reducing foreign production (and foreign emissions).

A further concern about compensating measures such as border carbon adjustments is that these may be abused as a substitute for trade policy and thus to bypass free trade agreements (Evenett & Whalley, 2009). Such compensation measures may therefore be in conflict with WTO rules. On the one hand, GATT provisions (in particular Articles I and III) are premised on outlawing discrimination in international trade. On the other hand, these rules have been interpreted as allowing border tax adjustments with respect to taxes on inputs which are "physically incorporated" into the final product. It is an open question whether energy can be interpreted as a physical input.⁵ However, many voices express doubts about legal compatibility and feasibility of BCA measures (cf. Cosbey, 2008; Fischer & Fox, 2009; Sabelström & Jegou, 2008; Stephenson & Upton, 2009).

Besides the legal difficulties with BCA measures their effectiveness and administrative feasibility is called into question. Effectiveness is challenged because firms may find a variety of ways to evade the controls imposed by BCA (Cosbey, 2008; Houser *et al.*, 2008). For instance, Houser *et al.* (2008) argue that a scheme that imposes border adjustment on Chinese steel may cause increased

⁵For a detailed discussion see OECD (2006), chapter 5, and Cosbey (2008).

flows from China to Japan, and increased flows from Japan to the U.S., without in the end protecting U.S. steel producers. Moreover, BCA measures are difficult to administer because it is far from obvious how to measure the carbon content in particular products (Cosbey, 2008). It is further questionable whether BCA measures provide an incentive for developing countries to implement domestic emission reduction measures. According to Sabelström & Jegou (2008), only a relatively small share of overall production in emerging economies would in fact be touched by BCA implemented in the USA and/or in the EU since most of the demand for energy-intensive products comes from the emerging countries themselves. Therefore, it is unlikely that BCA measures will significantly change the production methods in developing countries. Finally, BCA may even induce a carbon war between developed and developing countries and eventually redirect trade (Mandelson, 2006).

Before turning to the empirical evidence on the effects of emissions trading on competitiveness and carbon leakage, it is important to emphasize that a firm's (international) competitiveness depends on a multitude of factors such as labor costs, supply of skilled labor, proximity to product markets, market competition, ability to pass-on cost increases and trade costs (Ponssard & Walker, 2008; Sijm, 2005). The additional costs associated to emissions trading are probably not the most important of these factors. Therefore, as long as the costs caused by emissions trading are not too high, relocation decisions are less likely to occur, especially if the relevant industries are capital-intensive.

4.5 Empirical evidence

Most of the empirical studies analyzing the effects of emissions trading schemes on competitiveness focus on the European Emissions Trading Scheme, which is by far the largest greenhouse gas emission trading scheme in existence.⁶ In particular,

⁶Compared to the U.S. SO₂ cap-and-trade system, the EU-ETS is much larger in terms of the number of covered sources (about 11,500 in the EU versus 3,000 in the U.S.), the emissions cap (about 2000 million tons CO₂ in the EU versus 9 million tons SO₂ in the U.S.), and the value of distributed allowances (about 30,000 million Euro (at a price of 15 Euro/ton of CO₂) versus 4,000 million Euro (at a price of 550 USD/ton of SO₂ and an exchange rate of 1,25 USD/Euro.)) Source: Ellerman & Buchner (2007), own calculations.

detailed studies have been carried out at a national level for Germany and the United Kingdom (UK) by Graichen *et al.* (2008) and Hourcade *et al.* (2007), respectively. These studies assess the following issues:

- Which sectors are likely to face significant increases in direct or indirect costs due to the emissions trading scheme?
- Which sectors face high exposure to international trade and may thus be at risk of carbon leakage?

4.5.1 Sectors affected by direct and indirect cost increases through emissions trading

Graichen *et al.* (2008) and Hourcade *et al.* (2007) analyze the cost effects of emissions trading based on the concept of 'value at stake', which is defined as the sum of potential direct and indirect costs of a given industry in relation to its gross added value. The direct costs of an industry depend on the emission intensity of production, comprising energy and process emissions. The indirect costs depend on electricity consumption and the pass-through of CO₂ costs to electricity prices. Assuming full cost pass-through and an allowance price of 20 Euro per ton of CO₂, the studies find that for most industries covered by the EU-ETS the maximum value at stake is below two percent of gross added value. The industrial activities with a maximum value at stake of more than 10 percent are summarized in Table 4.1. Taken together, these activities represent roughly one percent of the gross domestic product in the UK and two percent of the gross domestic product in Germany.⁷ The different industry impacts in the two countries are partly due to structural differences in energy production. In the UK, the marginal power generation unit is provided by a natural gas-based power plant, while in Germany the marginal generation unit is usually a hard coal-based power plant. Since hard coal is more emission-intensive than natural gas, the indirect cost effect due to increasing electricity prices is higher in Germany than in the UK.

⁷Similar figures have been obtained by Bruyn *et al.* (2008) for the Netherlands, CISA (2008) for Australia, and both Morgenstern *et al.* (2007) and Aldy & Pizer (2009) for the USA.

Table 4.1: Potentially exposed industries under unilateral CO₂ pricing in Germany and the United Kingdom

Maximum value at stake (% of gross added value)	Germany	United Kingdom
> 50%	cement, lime	
> 40% – 50%		lime
> 30% – 40%		cement
> 20% – 30%	fertilizers & nitrogen	basic iron & steel
> 10% – 20%	basic iron & steel, aluminum, paper & paperboard, other basic inorganic chemicals, coke & refined petroleum products	refined petroleum products, aluminum, fertilizers & nitrogen,

Sources: Graichen *et al.* (2008); Hourcade *et al.* (2007).

4.5.2 Sectors affected by emissions trading due to international competition

High values at stake due to unilateral CO₂ pricing are not a matter of concern in industries facing a low degree of international competition. By contrast, increases in production costs as a result of unilateral climate policy in highly trade-exposed industries can distort competitive conditions in favor of international competitors from less regulated countries. This holds both for exports of domestic production to foreign markets and for import penetration in the domestic market. In the studies on Germany and the UK, trade intensity is used as a proxy for the intensity of international competition in a certain industry. Trade intensity (TI) is calculated by relating the sum of traded goods to the total market supply:

$$\text{Non EU TI} = \frac{\text{Non EU exports} + \text{Non EU imports}}{\text{Domestic output} + \text{EU imports} + \text{Non EU imports}}. \quad (4.1)$$

To measure trade intensity within the EU (4.1) changes to:

$$\text{EU TI} = \frac{\text{EU exports} + \text{EU imports}}{\text{Domestic output} + \text{EU imports} + \text{Non EU imports}}. \quad (4.2)$$

Clearly, trade intensity is only a rough indicator since the intensity of competition depends on many other factors such as transport costs, exchange rate uncertainty, product differentiation, and market segmentation. The analysis of trade intensities shows, however, that some of the sectors most affected by cost increases through exposure to emissions trading are not presently subject to strong international competition. For instance, the trade intensities for the lime and cement sectors, which are both heavily affected by carbon-related costs, are five percent or less in both Germany and the UK. Table 4.2 summarizes the industries in Germany and the UK with trade intensities of more than 10 percent.

4.5 Empirical evidence

Table 4.2: Trade intensities for different industrial sectors in Germany and the United Kingdom

Trade intensity	Germany	United Kingdom
> 50%	dyes & pigments	coke oven products, other textile weaving
> 40% – 50%		industrial gases
> 30% – 40%	other basic inorganic chemicals	
> 20% – 30%	other glass, copper products, aluminum	copper products, non-wovens, malt, aluminum, other basic inorganic chemicals, refined petroleum products
> 10% – 20%	paper & paperboard, veneer sheets, plastics, fertilizers & nitrogen, hollow glass, basic iron & steel, glass fibers, ceramic tiles	rubber tires & tubes, basic iron & steel, pulp & paper, veneer sheets, fertilizers & nitrogen, hollow glass

Sources: Graichen *et al.* (2008); Hourcade *et al.* (2007).

Bringing both indicators together, Graichen *et al.* (2008) and Hourcade *et al.* (2007) identify those industrial sectors with both values at stake and trade intensities of above 10 percent as being at risk of losing international competitiveness due to unilateral CO₂ pricing. In both Germany and the UK, these sectors are iron and steel, fertilizers and nitrogen, and aluminum and aluminum products. In addition, the German sectors for paper and paperboard and basic inorganic chemicals are exposed to losses in international competitiveness through CO₂ regulation, mainly because of the high indirect costs of electricity. In the UK, the sector for refined petroleum products is also facing the risk of losing competitive-

ness, mainly due to the high intensity of trade with non-EU countries. Altogether, Graichen *et al.* (2008) and Hourcade *et al.* (2007) suggest that only a relatively small number of sectors face a large risk of losing international competitiveness.

In fact, a study by Smale *et al.* (2006) analyzing the impact of emissions trading on firm profits and market prices indicates that most EU-ETS sectors are even expected to benefit in the first two trading periods, with prices and profits rising overall and only modest production drops in the steel and cement industries. The only exception is aluminum smelting, which is exposed both to large increases in marginal cost and to high levels of international competition, with potential relocation of production outside the EU as a consequence of emissions trading. The firms' potential for making substantial profits in the first two trading periods arises from the free allocation of emission allowances. Since allowance prices are added to the marginal production costs independently of whether allowances are auctioned off or allocated for free, there is a potential for "double compensation", as Grubb & Neuhoff (2006) call it.

Yet another study by Demailly & Quirion (2007) focuses on the competitiveness effects in the highly internationally exposed iron and steel industry. The authors suggest that this industry faces only small output reductions but a strong increase in profitability due to emissions trading in the EU. Even for a scenario where free allocation of allowances is reduced from 100 to 50 percent, the negative impact on profits is found to be very small. In fact, for the USA Goulder & Mathai (2000) find that on average only 13 percent of allowances had to be allocated for free to compensate firms for additional costs arising from greenhouse gas reductions.

4.5.3 Leakage effects

The issue of CO₂ emission leakage due to unilateral carbon pricing has been addressed in several simulation studies. In this context, a detailed analysis of the European cement industry by Demailly & Quirion (2006) shows that a significant leakage effect arises under free allocation based on historical emissions, compensating for about half of the emission reductions in the EU. Using a model of

global trade, Fischer & Fox (2009) simulate the effect of a unilateral CO₂ emission price of 50 U.S. dollar per ton of CO₂, implemented jointly by the United States and Canada. For different border adjustment policies they analyze the effects on competitiveness and leakage in several industrial sectors (i.e. electricity, refined petroleum products, chemicals, nonmetallic minerals, pulp and paper, and iron and steel). Fischer & Fox (2009) find that most adjustment policies are able to reduce the loss in production compared to a situation without adjustment. Moreover, full border tax adjustment and home rebates (output-based free allocation) turn out as the most effective policies. However, the authors also reveal that none of the policies is effective in reducing average leakage, defined as the change in foreign emissions relative to domestic emission reductions. For both the United States and Canada, leakage rates are considerable under all policies, ranging between ten percent (in the electricity sector) and 90 percent (in the refined petroleum products sector) in the United States and between 18 percent (in the pulp and paper sector) and 105 percent (in the refined petroleum products sector) in Canada.

An important caveat in connection with the analysis by Fischer & Fox (2009) is that it ignores existing climate policies in other countries, including the European Emissions Trading Scheme. Accordingly, the estimated leakage rates may be overstated. Moreover, analyzing competitiveness and leakage separately for different sectors ignores the fact that policies targeting a specific sector have important indirect effects on other closely connected sectors and ultimately on the (world) economy as a whole. In this context, several economy-wide studies show that leakage varies significantly depending on the size of country coalitions adopting comparable climate policies (see Dröge, 2009, for an overview). According to Dröge (2009), the typical leakage estimate is in the order of 20 percent. The challenge for future research is to develop comprehensive models that jointly analyze the effects of different policies on competitiveness, leakage, and overall emissions from all sectors (whether participating in emissions trading or not) and for all countries (domestic and foreign).

One such attempt has been made by Böhringer *et al.* (2010) who analyze the effects of a unilateral 20 percent reduction of CO₂ emissions in the U.S. and/or the EU, combined with several anti-leakage policies, on the global distribution

of welfare, competitiveness, and carbon leakage.⁸ They study different policy scenarios compared to a baseline case without any climate policies, namely (a) allowance auctioning and no anti-leakage policies, (b) output-based free allocation to energy-intensive industries, (c) rebates for energy-intensive exports, (d) tariffs on energy-intensive imports, and (e) a combination of export rebates and import tariffs. The main results by Böhringer *et al.* (2010) can be summarized as follows. First, they find that welfare losses do not only occur in countries pursuing climate policies but also in countries that are trading partners. In particular, the welfare loss is substantially higher in the EU than in the U.S., mainly because the U.S. has cheaper abatement options both concerning energy efficiency improvements and fuel switching in electricity production. Since EU countries are more trade-intensive, most other countries are worse off in the case of unilateral EU climate policy than under unilateral U.S. climate policy. Among the trading partners, the welfare effects are particularly negative in oil and coal exporting countries (e.g. Russia, the OPEC countries, Mexico) and may even be positive in oil and coal importing countries (e.g. India, Japan). This is because climate policy induces changes in global energy prices through the reduced demand for CO₂-intensive fossil fuels, which then leads to decreasing coal and crude oil prices and increasing natural gas prices.

The second result obtained by Böhringer *et al.* (2010) is that anti-leakage policies do not substantially decrease the welfare costs borne by the U.S. and/or the EU. In both the U.S. and the EU welfare costs are smallest under border adjustment policies. Conversely, the implementation border adjustment leads to large welfare costs in the other countries, particularly in countries exporting coal, crude oil, and energy-intensive goods. For the world as a whole, however, the differences in welfare costs arising from the alternative adjustment policies are negligible.

The third result put forward by Böhringer *et al.* (2010) is that global emission leakage is higher (up to 38 percent) when only the EU undertakes climate policy, as compared to the case where only the U.S. or both the EU and the U.S. reduce emissions (up to 19 and 22 percent, respectively). The reason is twofold. First, the European economy has a larger share of imports and exports than the U.S..

⁸Böhringer *et al.* (2010) also provide a brief overview of related studies.

Second, since energy-intensive industries in the EU are less emission-intensive than in the U.S., industrial relocation away from Europe implies a higher leakage rate. Moreover, in line with the findings of Fischer & Fox (2009), Reinaud (2005), and Burniaux *et al.* (2008) the different anti-leakage policies can only moderately reduce the global leakage effect in the model of Böhringer *et al.* (2010). The reason is that the largest share of leakage is caused by changing global fossil-fuel prices. Since an emission constraint in a particular country or region will lead to lower demand and thus lower prices for fossil fuels on the world market, other countries or regions without emission constraint will respond by increasing their demand for fossil fuels, thereby offsetting (a part of) the emission reductions. However, anti-leakage policies can only compensate rather imperfectly for indirect leakage effects through the energy market because they account for the CO₂ content of a particular product but cannot influence the changes in global demand and prices for fossil fuels.

Finally, in terms of the competitiveness effects in energy-intensive sectors, Böhringer *et al.* (2010) find that the production of chemical products, non-ferrous metals (and in the EU also iron and steel) is most strongly affected by unilateral climate policy, and that full border-adjustment policies can reduce the negative impacts on energy-intensive production to some extent. In the unregulated countries, the exports of energy-intensive goods mostly benefit from unilateral climate policy in the EU and/or the U.S., even when the most effective anti-leakage policies, i.e. import tariffs and full border adjustment, are in force. In addition, the regional impacts differ considerably, mainly driven by different carbon intensities in production and the use of different technologies and energy inputs.

Böhringer *et al.* (2010) nevertheless conclude that the controversial debate on anti-leakage policies overstates the importance of the leakage problem. According to their analysis, the main impacts on global welfare, emissions, and production are caused by the unilateral climate policy itself, i.e. the 20 percent reduction of CO₂ emissions in the U.S. and/or the EU. The authors claim that anti-leakage policies can mitigate the negative effects arising from the underlying climate policy objective only to a very limited extent, i.e. only in particular sectors or countries. In addition, they assert that developing countries do not

generally benefit from unilateral climate policies undertaken by developed countries because reductions both in energy demand and in energy-intensive imports will have negative effects, particularly in the fossil-fuel exporting countries. On the other hand, energy-intensive sectors in developing countries do not generally lose as a result of anti-leakage policies. They may even benefit from lower import prices for fossil fuels. These results are confirmed by several other general equilibrium studies finding that BCA measures indeed induce a global welfare decline and net benefits from reductions in carbon leakage are uncertain (Alexeeva-Talebi *et al.*, 2008; Burniaux *et al.*, 2008; Manders & Veenendaal, 2008).

4.6 Concluding remarks

In this chapter, we have analyzed the potential repercussions a system of tradable emission allowances may have on competitiveness of firms, regions, and countries both on the national and on the international level. Within the same trading system, such competitive distortions may be caused by unequal treatment of firms located in different jurisdictions, generating unequal sectoral burdens and inefficient abatement efforts. This applies to markets where firms operating in the same allowance market face different competitive conditions, as was (and still is) the case in the European Union under the first two trading phases of the EU-ETS. Such differential treatment may also occur when different industries in one jurisdiction are regulated under different policy instruments. The problem of competitive neutrality within the same allowance market but across different jurisdictions can best be solved through an auctioning system for allowances. Moreover, since tradable allowance systems create indirect costs via the pass-through to energy prices, countries with heterogeneous energy generation structures are differently affected by allowance trading.

A second source of competitive distortions may result from environmental policies of varying stringency, leading to international competitive disadvantages for industries located in countries or regions with stricter emission limits than others, because they cannot pass on the carbon costs to global market prices. This problem is not specific to allowance trading but would also arise if a different environmental policy were employed. The different stringency of envi-

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ronmental policies worldwide may also give rise to carbon leakage if production costs increase in countries with stricter emission targets and production thus is shifted to countries with less strict emission targets or none at all. In the long run, (re)investment may also move from countries with tight emission policies to those with little or no regulation. Carbon leakage may also occur via the energy market because lower demand for energy in countries with strict emission policies tends to push down energy prices, thereby increasing energy demand in other parts of the world. Finally, there is also a risk of intertemporal leakage. This type of leakage arises when the announcement of tighter climate policy on a worldwide scale causes fossil-fuel source owners to speed up resource exploitation in order to sell as much of their fossil-fuel resources as possible before emission caps are implemented worldwide (Sinn, 2008).⁹ Carbon leakage effects may be considerable, and while there is debate about the total size of leakage, it could range from almost zero to more than 100 percent, depending on the industrial sector. Countermeasures to mitigate carbon leakage, including free allowance allocation and border-carbon-adjustment measures have only limited impact since a large part of the leakage effect is caused by changes in global energy prices. In addition, the most effective policy measures in addressing the leakage problem may not be effective in addressing the international competitiveness issues. Unfortunately, the problem of large stringency differences in environmental policy across countries cannot be solved in a perfectly satisfactory way by unilateral policies. Therefore, solving the problems related to international competitiveness and leakage ultimately requires more and better international coordination.

⁹We have not touched upon intertemporal leakage in detail because it does not give rise to the sort of competitive distortions considered in this chapter.

Conclusions

In this thesis I have studied various facets of carbon mitigation policies. In Chapter 1, I have examined the optimal design of a tax-subsidy policy taking into account pollution and market power in the fossil-fuel energy sector and learning spill-overs and market power in the renewable energy industry. In Chapter 2, the dynamic interactions between emission allowance and energy prices and their application to portfolio allocation have been assessed. In Chapter 3, I have investigated the different forms and potential impacts of market manipulations due to market power in emissions trading schemes. Finally, I have scrutinized the potential distortions of (inter)national competitiveness arising through emissions trading in Chapter 4. In the following, I will provide some general conclusions and policy recommendations.

The results obtained in the first chapter indicate that currently implemented feed-in tariff policies to increase the share of renewable energies are highly inefficient for several reasons. The first efficiency problem arises because feed-in tariffs promote the generation of renewable energies, whereas the learning effects presumably occur in the production of renewable energy equipment such as wind turbines and solar panels. From an economic point of view only the learning spill-overs arising from renewable equipment production should be subsidized because the firms already take into account the cost reductions they may achieve through private (i.e. firm-specific) learning. The second efficiency problem is caused by overlapping regulations. In many countries, for instance in Europe, feed-in tariffs coexist with emissions trading systems. However, the cap on total emissions implemented through these systems fully compensates for the additional emission-reducing effect through renewable energy generation. The efficiency losses through overlapping regulations may be solved by implementing

an emission tax instead of emissions trading. However, the results in the first chapter show that, when combined with an emission tax in the fossil-fuel sector, second-best optimal feed-in tariffs have a very complicated structure and do not provide considerable increases in social welfare compared to a pure emission tax policy. The reason is that the learning spill-over effects in the renewable energy industry are largely dominated by the effects caused through imperfect competition in the fossil-fuel sector. In the model presented in Chapter 1, I have analyzed a feed-in tariff that is not differentiated according to the type of renewable technology. I expect, however, that incorporating this additional feature would further increase both the complexity and the inefficiency of this instrument. By contrast, if the regulator raises the tax rate or tightens the emission cap, increasing emission prices would "automatically" improve the competitive position of renewable energies vis-à-vis conventional energies.

The results of the second chapter indicate that the European emission market has matured considerably in the second period of emission allowance trading. In the first trading period from 2005-2007 allowance prices were largely influenced by issues related to the design of the trading system such as the excess allocation of emission allowances to the firms, whereas the influence of energy prices and other fundamental allowance price drivers was rather weak and did not hold consistently throughout the complete period. In the second trading period I find that a stable long-run equilibrium relationship exists between emission allowance and energy prices, namely electricity, natural gas, and coal. Moreover, it is interesting from a policy perspective that the effect of increasing coal prices on electricity prices in the short run is absorbed to some extent by a decrease in allowance prices. The reason is that increasing costs for coal drive down demand for emission allowances. This dampening effect on wholesale electricity prices can be seen as an advantage of emissions trading over emission taxes (as an alternative policy instrument to regulate emissions). Since emission tax rates are fixed by the regulator, they are not able to react to unexpected fuel price shocks. In times of considerably increasing fossil-fuel prices this positive side-effect of emissions trading could potentially lower the financial burden imposed on electricity-intensive industries and households compared to an alternative regulation through emission taxes.

The results in the third and fourth chapter point out numerous sources for potential distortions on emission allowance markets such as distortions arising from market power and through unequal regulation across firms, industries, or countries. The potential for anti-competitive effects due to market power is an important issue in the context of emissions trading. Therefore, competition authorities should observe emission markets especially when the number of participants is relatively small. Moreover, a careful design of the essential rules of the trading system can help to prevent anti-competitive behavior. In particular, policy makers should try to make sure that the allocation rules for allowances, both through auctioning or free allocation, do not provide incentives for strategic bidding behavior, strategic detention and strategic sale of allowances, that there is a standardized price-setting mechanism leading to a unique allowance price, and that transparent trading rules are established, guaranteeing liquid spot and secondary markets.

In the context of unequal regulation across firms, industries, and countries not all of the distortions are inherent to emissions trading. For instance, independent of whether emissions are regulated through tradable allowances, taxes, standards, or other instruments, a varying stringency of the regulation will give rise to deviations between the marginal abatement costs of the affected entities and thus lead to higher than optimal total costs of the policy. The empirical evidence for Europe indicates that in general terms the impact of emissions trading on the international competitiveness of firms is still relatively small. In fact, competitiveness is influenced by a wide range of factors, among which the carbon constraint is, at least currently, probably not the most important one.

Distortions through unequal treatment on the international level can lead to considerable carbon leakage. For the time being there is no clear picture concerning the overall magnitude of carbon leakage. Estimating the rate of carbon leakage is difficult because leakage may occur through different channels, directly through the emission constraint and indirectly through changes in global energy prices. Since changing energy prices also affect countries without proper climate policy, these countries do not necessarily benefit from unilateral climate policies elsewhere. Moreover, there is no unilateral measure to perfectly compensate for both international competitive distortions and leakage. The best remedy to tackle

both problems would be to enlarge the coalition of countries engaging in climate policy. Within a trading system, competitive neutrality and cost-efficiency can best be achieved by allocating emission allowances through auctions, as long as the auction mechanism does not provide incentives for anti-competitive behavior of large firms.

Taken all the results presented in this thesis together, it becomes clear that no single policy instrument can possibly achieve all desired climate policy objectives together, while being both economically efficient and effective in terms of reaching the policy target. Therefore, as long as there are as diverse and often conflicting policy targets as currently observed in many countries, there will always be a trade-off between efficiency and effectiveness of a given policy. One example for such a policy conflict is the 20-20-20 target in the European Union, consisting of a 20 percent cut in emissions, a 20 percent share of renewable energies, and a 20 percent increase in energy efficiency, to be achieved until 2020. On the one hand, effectiveness in terms of meeting the 20-20-20 target will necessarily be to the detriment of economic efficiency, because the instruments employed to increase production of renewable energies and to improve energy efficiency will have a counterproductive effect on the European emission allowance market. On the other hand, the current market price for CO₂ emission allowances in Europe of roughly 16€/ton CO₂ indicates the availability of much cheaper abatement options compared to, for instance, most currently available renewable energy technologies. A market-based climate policy approach through either emission taxes or a system of tradable emission allowances would allow firms to first exploit the cost-effective emission abatement potentials before moving to higher-cost options such as renewable energy production. Therefore, such an approach would ensure economic efficiency of the climate policy and, in the medium to long term, also lead to the achievement of other policy objectives besides the reduction of emissions.

Appendix A

Appendix A

A.1 Proof of the comparative-static effects of market concentration with oligopolistic competition in the fossil-fuel industry only

In order to analyze the impact of market structure in the fossil-fuel industry on output, prices and the policy instruments we differentiate equations (1.2)–(1.4), and (1.13)–(1.19) with respect to the number of fossil fuel utilities. Simplifying via the envelope theorem then yields the following system of equations:

Aggregate electricity production:

$$\frac{\partial Q_1}{\partial m} = \int_0^{X_1} \frac{\partial q_1(\tilde{x})}{\partial m} d\tilde{x} + q_1(X_1) \frac{\partial X_1}{\partial m} + m \frac{\partial k_1}{\partial m} + k_1 \quad (\text{A.1})$$

$$\frac{\partial Q_2}{\partial m} = \int_0^{X_2} \frac{\partial q_2(\tilde{x})}{\partial m} d\tilde{x} + q_2(X_2) \frac{\partial X_2}{\partial m} + m \frac{\partial k_2}{\partial m} + k_2 \quad (\text{A.2})$$

Electricity production of the intra-marginal RES-E firms:

$$\frac{\partial q_1(\tilde{x})}{\partial m} = \frac{P'_1(Q_1)}{C_{qq}^1(q_1(\tilde{x}), \tilde{x})} \frac{\partial Q_1}{\partial m} \quad \forall \tilde{x} \leq X_1 \quad (\text{A.3})$$

$$\frac{\partial q_2(\tilde{x})}{\partial m} = \frac{P'_2(Q_2)}{C_{qq}^2(q_2(\tilde{x}), \tilde{x})} \frac{\partial Q_2}{\partial m} \quad \forall \tilde{x} \leq X_2 \quad (\text{A.4})$$

A.1 Proof of the comparative-static effects of market concentration with oligopolistic competition in the fossil-fuel industry only

Electricity production of the fossil fuel utilities:

$$0 = [P'_1(Q_1) + P''_1(Q_1)k_1] \frac{\partial Q_1}{\partial m} + [P'_1(Q_1) - K''_1(k_1)] \frac{\partial k_1}{\partial m} - \frac{\partial \tau_1}{\partial m} \quad (\text{A.5})$$

$$0 = [P'_2(Q_2) + P''_2(Q_2)k_2] \frac{\partial Q_2}{\partial m} + [P'_2(Q_2) - K''_2(k_2)] \frac{\partial k_2}{\partial m} - \frac{\partial \tau_2}{\partial m} \quad (\text{A.6})$$

Production of the RES-E equipment firms:

$$0 = \frac{\partial b_1}{\partial m} - [\Gamma^1_{y_1 y_1} + \delta \Gamma^2_{LL}(1 + (n-1)\varepsilon)] \frac{\partial y_1}{\partial m} + \frac{\partial \sigma_1}{\partial m} - \delta \Gamma^2_{y_2 L} \frac{\partial y_2}{\partial m} \quad (\text{A.7})$$

$$0 = \frac{\partial b_2}{\partial m} - \Gamma^2_{y_2 y_2} \frac{\partial y_2}{\partial m} - \Gamma^2_{y_2 L}(1 + (n-1)\varepsilon) \frac{\partial y_1}{\partial m} \quad (\text{A.8})$$

Emission taxes:

$$\frac{\partial \tau_1}{\partial m} = P''_1(Q_1)k_1 \frac{\partial Q_1}{\partial m} + [P'_1(Q_1) + mD''_1(mk_1)] \frac{\partial k_1}{\partial m} + D''_1(mk_1)k_1 \quad (\text{A.9})$$

$$\frac{\partial \tau_2}{\partial m} = P''_2(Q_2)k_2 \frac{\partial Q_2}{\partial m} + [P'_2(Q_2) + mD''_2(mk_2)] \frac{\partial k_2}{\partial m} + D''_2(mk_2)k_2 \quad (\text{A.10})$$

Output subsidy for the RES-E equipment firms:

$$\frac{\partial \sigma_1}{\partial m} = -\delta(n-1)\varepsilon \Gamma^2_{LL}(1 + (n-1)\varepsilon) \frac{\partial y_1}{\partial m} - \delta(n-1)\varepsilon \Gamma^2_{y_2 L} \frac{\partial y_2}{\partial m} \quad (\text{A.11})$$

Total number of RES-E equipment:

$$\frac{\partial X_1}{\partial m} = n \frac{\partial y_1}{\partial m} \quad (\text{A.12})$$

$$\frac{\partial X_2}{\partial m} = n \frac{\partial y_2}{\partial m} \quad (\text{A.13})$$

Electricity prices:

$$\frac{\partial p_1}{\partial m} = P'_1(Q_1) \frac{\partial Q_1}{\partial m} \quad (\text{A.14})$$

$$\frac{\partial p_2}{\partial m} = P'_2(Q_2) \frac{\partial Q_2}{\partial m} \quad (\text{A.15})$$

A.1 Proof of the comparative-static effects of market concentration with oligopolistic competition in the fossil-fuel industry only

RES-E equipment prices:

$$\frac{\partial b_1}{\partial m} = P'_1(Q_1)q_1(X_1)\frac{\partial Q_1}{\partial m} - C_{X_1}^1\frac{\partial X_1}{\partial m} \quad (\text{A.16})$$

$$\frac{\partial b_2}{\partial m} = P'_2(Q_2)q_2(X_2)\frac{\partial Q_2}{\partial m} - C_{X_2}^2\frac{\partial X_2}{\partial m} \quad (\text{A.17})$$

Substituting $\frac{\partial q_1(\tilde{x})}{\partial m}$ and $\frac{\partial q_2(\tilde{x})}{\partial m}$ from (A.3) and (A.4) into (A.1) and (A.2) leads to the following expressions for the change in aggregate electricity production:

$$\frac{\partial Q_1}{\partial m} = \frac{1}{1 - P'_1(Q_1)CC_1} \left[m\frac{\partial k_1}{\partial m} + q_1(X_1)\frac{\partial X_1}{\partial m} + k_1 \right] \quad (\text{A.18})$$

$$\frac{\partial Q_2}{\partial m} = \frac{1}{1 - P'_2(Q_2)CC_2} \left[m\frac{\partial k_2}{\partial m} + q_2(X_2)\frac{\partial X_2}{\partial m} + k_2 \right], \quad (\text{A.19})$$

where $CC_1 = \int_0^{X_1} \frac{1}{C_{q_1}^1(q_1(\tilde{x}), \tilde{x})} d\tilde{x}$ and $CC_2 = \int_0^{X_2} \frac{1}{C_{q_2}^2(q_2(\tilde{x}), \tilde{x})} d\tilde{x}$. We can now write the system of equations in matrix form and solve for the comparative-static effects. We assume that $\Gamma_{Ly_2}^2$ is sufficiently small, which together with Condition 1 implies that the effect of learning on the marginal costs of RES-E equipment producers in the second period is not too large. We can then unambiguously sign the effects as follows, where Det denotes the determinant of the matrix:

$$\begin{aligned} Det = & \frac{1}{Det} C_{qq}^1 C_{qq}^2 \left\{ \left[(\Gamma_{y_1 y_1}^1 + C_{X_1}^1 n) [(K_1'' + mD_1'')(P_1'CC_1 - 1) + mP_1'] \right. \right. \\ & + n(K_1'' + mD_1'')P_1'q_1^2 \left. \right] \left[(\Gamma_{y_2 y_2}^2 + C_{X_2}^2 n) [(K_2'' + mD_2'')(P_2'CC_2 - 1) + mP_2'] \right. \\ & + n(K_2'' + mD_2'')P_2'q_2^2 \left. \right] + \delta(1 + (n-1)\varepsilon)^2 [(K_1'' + mD_1'')(P_1'CC_1 - 1) + mP_1'] \\ & \underbrace{\left[(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{y_2 L}^2)^2) [(K_2'' + mD_2'')(P_2'CC_2 - 1) + mP_2'] \right]}_{\text{Condition 1}} \\ & \left. + \Gamma_{LL}^2 C_{X_2}^2 n [(K_2'' + mD_2'')(P_2'CC_2 - 1) + mP_2'] + \Gamma_{LL}^2 n (K_2'' + mD_2'') P_2' q_2^2 \right\} > 0 \end{aligned}$$

**A.1 Proof of the comparative-static effects of market concentration
with oligopolistic competition in the fossil-fuel industry only**

$$\begin{aligned}
\frac{\partial k_1}{\partial m} &= -\frac{1}{Det} C_{qq}^1 C_{qq}^2 \left\{ \left[(\Gamma_{y_2 y_2}^2 + C_X^2 n) ((K_2'' + m D_2'') (P_2' C C_2 - 1) + m P_2') \right. \right. \\
&\quad \left. \left. + (K_2'' + m D_2'') n P_2' q_2^2 \right] \left[D_1'' k_1 [(\Gamma_{y_1 y_1}^1 + n C_X^1) (P_1' C C_1 - 1) + n P_1' q_1^2] \right. \right. \\
&\quad \left. \left. + P_1' k_1 (\Gamma_{y_1 y_1}^1 + C_X^1 n) \right] + \delta (1 + (n - 1) \varepsilon)^2 \overbrace{(\Gamma_{LL}^2 (\Gamma_{y_2 y_2}^2 + C_X^2 n) - (\Gamma_{y_2 L}^2)^2)}^{\text{Condition 1}} \right. \\
&\quad \left. [(K_2'' + m D_2'') (P_2' C C_2 - 1) + m P_2'] [(P_1' C C_1 - 1) - P_1' k_1] \right. \\
&\quad \left. + \delta (1 + (n - 1) \varepsilon)^2 \Gamma_{LL}^2 k_1 (K_2'' + D_2'' m) n P_2' q_2^2 [D_1'' (P_1' C C_1 - 1) + P_1'] \right. \\
&\quad \left. + \delta (1 + (n - 1) \varepsilon) \Gamma_{y_2 L}^2 k_2 K_2'' n P_1' P_2' q_1 q_2 \right\} < 0 \\
\frac{\partial k_2}{\partial m} &= -\frac{1}{Det} C_{qq}^1 C_{qq}^2 \left\{ [(K_1'' + m D_1'') (P_1' C C_1 - 1) + m P_1'] [P_2' + D_2'' (P_2' C C_2 - 1)] \right. \\
&\quad \left. \left[\Gamma_{y_1 y_1}^1 k_2 (\Gamma_{y_2 y_2}^2 + C_X^2 n) + \delta (1 + (n - 1) \varepsilon)^2 \overbrace{(\Gamma_{LL}^2 (\Gamma_{y_2 y_2}^2 + C_X^2 n) - (\Gamma_{y_2 L}^2)^2)}^{\text{Condition 1}} \right] \right. \\
&\quad \left. + (\Gamma_{y_2 y_2}^2 + C_X^2 n) n k_2 [P_2' + D_2'' (P_2' C C_2 - 1)] \right. \\
&\quad \left. \left[C_X^1 (K_1'' + D_1'' m) ((P_1' C C_1 - 1) + P_1' q_1^2) + C_X^1 m P_1' \right] \right. \\
&\quad \left. + D_2'' k_2 n P_2' q_2^2 \left[\Gamma_{y_1 y_1}^1 [(K_1'' + D_1'' m) (P_1' C C_1 - 1) + m P_1'] \right. \right. \\
&\quad \left. \left. + n [C_X^1 (K_1'' + D_1'' m) ((P_1' C C_1 - 1) + P_1' q_1^2) + C_X^1 m P_1'] \right. \right. \\
&\quad \left. \left. + \delta (1 + (n - 1) \varepsilon)^2 \Gamma_{LL}^2 [(K_1'' + m D_1'') (P_1' C C_1 - 1) + m P_1'] \right] \right. \\
&\quad \left. + (1 + (n - 1) \varepsilon) \Gamma_{y_2 L}^2 k_1 K_1'' n P_1' P_2' q_1 q_2 \right\} < 0 \\
\frac{\partial q_1(\tilde{x})}{\partial m} &= -\frac{1}{Det} C_{qq}^2 P_1' \left\{ [k_1 K_1'' (\Gamma_{y_1 y_1}^1 + C_X^1 n)] \right. \\
&\quad \left. \left[(\Gamma_{y_2 y_2}^2 + C_X^2 n) ((K_2'' + m D_2'') (P_2' C C_2 - 1) + m P_2') + (K_2'' + D_2'' m) n P_2' q_2^2 \right] \right. \\
&\quad \left. + \delta (1 + (n - 1) \varepsilon) \left[(1 + (n - 1) \varepsilon) k_1 K_1'' \overbrace{(\Gamma_{LL}^2 (\Gamma_{y_2 y_2}^2 + C_X^2 n) - (\Gamma_{y_2 L}^2)^2)}^{\text{Condition 1}} \right. \right. \\
&\quad \left. \left. [(K_2'' + m D_2'') (P_2' C C_2 - 1) + m P_2'] + \Gamma_{LL}^2 k_1 K_1'' (1 + (n - 1) \varepsilon) (K_2'' + D_2'' m) n P_2' q_2^2 \right. \right. \\
&\quad \left. \left. + \Gamma_{y_2 L}^2 k_2 K_2'' (K_1'' + D_1'' m) n P_2' q_1 q_2 \right] \right\} < 0 \\
\frac{\partial q_2(\tilde{x})}{\partial m} &= -\frac{1}{Det} C_{qq}^1 P_2' \left\{ [(K_1'' + m D_1'') (P_1' C C_1 - 1) + m P_1'] \right. \\
&\quad \left. \left[\Gamma_{y_1 y_1}^1 k_2 K_2'' (\Gamma_{y_2 y_2}^2 + C_X^2 n) + \delta (1 + (n - 1) \varepsilon)^2 k_2 K_2'' \overbrace{(\Gamma_{LL}^2 (\Gamma_{y_2 y_2}^2 + C_X^2 n) - (\Gamma_{y_2 L}^2)^2)}^{\text{Condition 1}} \right. \right. \\
&\quad \left. \left. + k_2 K_2'' n (\Gamma_{y_2 y_2}^2 + C_X^2 n) [C_X^1 [(K_1'' + D_1'' m) (C C_1 - P_1') + m P_1']] \right. \right. \\
&\quad \left. \left. + \Gamma_{y_2 L}^2 K_1'' k_1 (1 + (n - 1) \varepsilon) (K_2'' + D_2'' m) P_1' q_1 q_2 n \right] \right\} < 0
\end{aligned}$$

**A.1 Proof of the comparative-static effects of market concentration
with oligopolistic competition in the fossil-fuel industry only**

$$\begin{aligned}
\frac{\partial Q_1}{\partial m} &= -\frac{1}{Det} C_{qq}^1 C_{qq}^2 \left\{ k_1 K_1'' (\Gamma_{y_1 y_1}^1 + C_X^1 n) \right. \\
&\quad \left[(\Gamma_{y_2 y_2}^2 + C_X^2 n) [(K_2'' + m D_2'') (P_2' C C_2 - 1) + m P_2'] + (K_2'' + m D_2'') n P_2' q_2^2 \right] \\
&\quad \overbrace{+ \delta(1 + (n-1)\varepsilon) \left[k_1 K_1'' (1 + (n-1)\varepsilon) (\Gamma_{LL}^2 (\Gamma_{y_2 y_2}^2 + C_X^2 n) - (\Gamma_{y_2 L}^2)^2) \right]}^{\text{Condition 1}} \\
&\quad \left. \left[(K_2'' + m D_2'') (P_2' C C_2 - 1) + m P_2' \right] + (1 + (n-1)\varepsilon) \Gamma_{LL}^2 k_1 K_1'' (K_2'' + D_2'' m) n P_2' q_2^2 \right. \\
&\quad \left. + \Gamma_{y_2 L}^2 k_2 K_2'' (K_1'' + D_1'' m) n P_2' q_1 q_2 \right\} > 0 \\
\frac{\partial Q_2}{\partial m} &= -\frac{1}{Det} C_{qq}^1 C_{qq}^2 \left\{ k_2 K_2'' [(K_1'' + m D_1'') (P_1' C C_1 - 1) + m P_1'] \right. \\
&\quad \overbrace{+ \delta(1 + (n-1)\varepsilon) \left[\Gamma_{LL}^2 (\Gamma_{y_2 y_2}^2 + C_X^2 n) - (\Gamma_{y_2 L}^2)^2 \right]}^{\text{Condition 1}} \\
&\quad \left. \left[\Gamma_{y_1 y_1}^1 (\Gamma_{y_2 y_2}^2 + C_X^2 n) + \delta(1 + (n-1)\varepsilon) \left(\Gamma_{LL}^2 (\Gamma_{y_2 y_2}^2 + C_X^2 n) - (\Gamma_{y_2 L}^2)^2 \right) \right] \right. \\
&\quad \left. + k_2 K_2'' n (\Gamma_{y_2 y_2}^2 + C_X^2 n) \left[(K_1'' + D_1'' m) [C_X^1 (P_1' C C_1 - 1) + P_1' q_1^2 + C_X^1 P_1' m] \right] \right. \\
&\quad \left. + (1 + (n-1)\varepsilon) \Gamma_{y_2 L}^2 k_1 K_1'' (K_2'' + D_2'' m) n P_1' q_1 q_2 \right\} > 0 \\
\frac{\partial y_1}{\partial m} &= -C_{qq}^1 C_{qq}^2 \left\{ k_1 K_1'' P_1' q_1 (\Gamma_{y_2 y_2}^2 + C_X^2 n) [(K_2'' + m D_2'') (P_2' C C_2 - 1) + m P_2'] \right. \\
&\quad - \delta \Gamma_{y_2 L}^2 k_2 K_2'' (1 + (n-1)\varepsilon) P_2' q_2 [(K_1'' + m D_1'') (P_1' C C_1 - 1) + m P_1'] \\
&\quad \left. + k_1 K_1'' (K_2'' + D_2'' m) n P_1' P_2' q_1 q_2^2 \right\} < 0 \\
\frac{\partial y_2}{\partial m} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 \left\{ \Gamma_{y_2 L}^2 k_1 K_1'' (1 + (n-1)\varepsilon) P_1' q_1 [(K_2'' + m D_2'') (P_2' C C_2 - 1) + m P_2'] \right. \\
&\quad - k_2 K_2'' P_2' q_2 \left[\Gamma_{y_1 y_1}^1 + \delta(1 + (n-1)\varepsilon)^2 \Gamma_{LL}^2 + C_X^1 n \right] \\
&\quad \left. \left[(K_1'' + m D_1'') (P_1' C C_1 - 1) + m P_1' \right] + (K_1'' + D_1'' m) n P_1' q_1^2 \right\} < 0 \\
\frac{\partial b_1}{\partial m} &= -\frac{1}{Det} C_{qq}^1 C_{qq}^2 \left\{ [(K_2'' + m D_2'') (P_2' C C_2 - 1) + m P_2'] \right. \\
&\quad \left[\Gamma_{y_1 y_1}^1 k_1 K_1'' P_1' q_1 (\Gamma_{y_2 y_2}^2 + C_X^2 n) + \delta(1 + (n-1)\varepsilon)^2 k_1 K_1'' P_1' q_1 \right. \\
&\quad \overbrace{\left. (\Gamma_{LL}^2 (\Gamma_{y_2 y_2}^2 + C_X^2 n) - (\Gamma_{y_2 L}^2)^2) \right]}^{\text{Condition 1}} \\
&\quad \left. + (K_2'' + D_2'' m) n P_1' P_2' q_1 q_2^2 k_1 K_1'' \right. \\
&\quad \left. \left[\Gamma_{y_1 y_1}^1 + (1 + (n-1)\varepsilon) \Gamma_{LL}^2 \right] + \delta(1 + (n-1)\varepsilon) k_2 K_2'' n P_2' q_2 \Gamma_{y_2 L}^2 \right. \\
&\quad \left. \left[(K_1'' + D_1'' m) (C_X^1 (P_1' C C_1 - 1) + P_1' q_1^2) + C_X^1 P_1' m \right] \right\} < 0 \\
\frac{\partial b_2}{\partial m} &= -\frac{1}{Det} C_{qq}^1 C_{qq}^2 \left\{ [K_1'' (P_1' C C_1 - 1) + m (P_1' + D_1'' (P_1' C C_1 - 1))] P_2' q_2 k_2 K_2'' \right. \\
&\quad \overbrace{\left. (\Gamma_{LL}^2 (\Gamma_{y_2 y_2}^2 + C_X^2 n) - (\Gamma_{y_2 L}^2)^2) \right]}^{\text{Condition 1}} \\
&\quad \left. \left[\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + n C_X^1 \Gamma_{y_2 y_2}^2 + \delta(1 + (n-1)\varepsilon)^2 (\Gamma_{LL}^2 (\Gamma_{y_2 y_2}^2 + C_X^2 n) - (\Gamma_{y_2 L}^2)^2) \right] \right. \\
&\quad \left. + P_1' P_2' q_1^2 q_2 n \Gamma_{y_2 y_2}^2 k_2 K_2'' (K_1'' + D_1'' m) + (1 + (n-1)\varepsilon) \Gamma_{y_2 L}^2 k_1 K_1'' n P_1' q_1 \right. \\
&\quad \left. \left[(K_2'' + D_2'' m) q_2 + C_X^2 [(K_2'' + m D_2'') (P_2' C C_2 - 1) + m P_2'] \right] \right\} < 0
\end{aligned}$$

A.1 Proof of the comparative-static effects of market concentration with oligopolistic competition in the fossil-fuel industry only

In order to unambiguously sign the comparative-static effects on the emission tax rates we further assume that $\Gamma_{Ly_2}^2$ is sufficiently small, which together with Condition 1 implies that the effect of learning on the marginal cost of RES-E equipment producers in the second period is not too large:

$$\begin{aligned}
\frac{\partial \tau_1}{\partial m} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 \left\{ \left[-((P_1')^2 + k_1 K_1'' P_1'') (\Gamma_{y_1 y_1}^1 + C_X^1 n) k_1 + D_1'' k_1 (K_1'' - P_1') \right. \right. \\
&\quad \left. \left[\Gamma_{y_1 y_1}^1 (P_1' C C_1 - 1) + n (C_X^1 (P_1' C C_1 - 1) + P_1' q_1^2) \right] \right. \\
&\quad \left. \left[(\Gamma_{y_2 y_2}^2 + C_X^2 n) [(K_2'' + m D_2'') (P_2' C C_2 - 1) + m P_2'] + (K_2'' + m D_2'') n P_2' q_2^2 \right] \right. \\
&\quad \left. \underbrace{\delta(1 + (n-1)\varepsilon)^2 k_1 (\Gamma_{LL}^2 (\Gamma_{y_2 y_2}^2 + C_X^2 n) - (\Gamma_{y_2 L}^2)^2)}_{\text{Condition 1}} \right. \\
&\quad \left. [K_2'' (P_2' C C_2 - 1) + m (P_2' + D_2'' (P_2' C C_2 - 1))] \right. \\
&\quad \left. [-((P_1')^2 + k_1 K_1'' P_1'') + (K_1'' - P_1') (P_1' C C_1 - 1) \right. \\
&\quad \left. + \Gamma_{y_2 L}^2 k_2 K_2'' n P_2' q_1 q_2 [-((P_1')^2 + k_1 K_1'' P_1'') + \delta(1 + (n-1)\varepsilon) m (P_1' + P_1'' k_1)] \right. \\
&\quad \left. + \Gamma_{LL}^2 k_1 (1 + (n-1)\varepsilon) (K_2'' + D_2'' m) n P_2' q_2^2 \right. \\
&\quad \left. [-((P_1')^2 + k_1 K_1'' P_1'') + \delta(1 + (n-1)\varepsilon) (K_1'' - P_1') (P_1' C C_1 - 1)] \right\} > 0 \\
\frac{\partial \tau_2}{\partial m} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 \left\{ [(K_1'' + m D_1'') (P_1' C C_1 - 1) + m P_1'] \right. \\
&\quad \left. [-((P_2')^2 + k_2 K_2'' P_2'') [\Gamma_{y_1 y_1}^1 k_2 (\Gamma_{y_2 y_2}^2 + C_X^2 n) + \delta(1 + (n-1)\varepsilon)^2 k_2 \right. \\
&\quad \left. \underbrace{(\Gamma_{LL}^2 (\Gamma_{y_2 y_2}^2 + C_X^2 n) - (\Gamma_{y_2 L}^2)^2)}_{\text{Condition 1}}] + D_2'' k_2 (K_2'' - P_2') \right. \\
&\quad \left. [[(\Gamma_{y_2 y_2}^2 + C_X^2 n) (P_2' C C_2 - 1) + n P_2' q_2^2] (\Gamma_{y_1 y_1}^1 + C_X^1 n) \right. \\
&\quad \left. \underbrace{\delta(1 + (n-1)\varepsilon)^2 [(\Gamma_{LL}^2 (\Gamma_{y_2 y_2}^2 + C_X^2 n) - (\Gamma_{y_2 L}^2)^2) (P_2' C C_2 - 1) + \Gamma_{LL}^2 n P_2' q_2^2]}_{\text{Condition 1}} \right. \\
&\quad \left. + (K_1'' + D_1'' m) k_2 n (\Gamma_{y_2 y_2}^2 + C_X^2 n) [-((P_2')^2 + k_2 K_2'' P_2'') \right. \\
&\quad \left. [((P_1' C C_1 - 1) + m P_1') C_X^1 + P_1' q_1^2] + D_2'' P_1' q_1^2 (K_2'' - P_2') (P_2' C C_2 - 1) \right. \\
&\quad \left. + D_2'' n^2 P_1' P_2' q_1^2 q_2^2 k_2 (K_1'' + D_1'' m) (K_2'' - P_2') + \Gamma_{y_2 L}^2 (1 + (n-1)\varepsilon) k_1 K_1'' n P_1' q_1 q_2 \right. \\
&\quad \left. [-((P_2')^2 + k_2 K_2'' P_2'') + D_2'' m (P_2' + P_2'' k_2)] \right\} > 0
\end{aligned}$$

The sign of the comparative-static effect on the subsidy in the RES-E equipment industry is ambiguous and Appendix A.2 further explores this ambiguity by providing a numerical example where both cases (positive and negative sign of the

A.2 The ambiguity of the comparative-static effect $\partial\sigma_1/\partial m$

variation of the subsidy rate) can occur:

$$\begin{aligned} \frac{\partial\sigma_1}{\partial m} = & \frac{1}{Det} C_{qq}^1 C_{qq}^2 \delta\varepsilon(n-1) \left\{ k_1 K_1'' (1 + (n-1)\varepsilon) \right. \\ & \overbrace{(\Gamma_{LL}^2 (\Gamma_{y_2 y_2}^2 + C_X^2 n) - (\Gamma_{y_2 L}^2)^2)}^{\text{Condition 1}} P_1' q_1 [(K_2'' + m D_2'') (P_2' C C_2 - 1) + m P_2'] \\ & + \Gamma_{LL}^2 k_1 K_1'' (1 + (n-1)\varepsilon) (K_2'' + D_2'' m) n P_1' P_2' q_1 q_2^2 + \Gamma_{y_2 L}^2 k_2 K_2'' P_2' \\ & \left. [(\Gamma_{y_1 y_1}^1 + C_X^1 n) [(K_1'' + m D_1'') (P_1' C C_1 - 1) + m P_1'] + (K_1'' + D_1'' m) n P_1' q_1^2] \right\} \leq 0 \end{aligned}$$

A.2 The ambiguity of the comparative-static effect $\partial\sigma_1/\partial m$

In order to assess the ambiguous sign of $\partial\sigma_1/\partial m$, we numerically simulate the system of equations given by (1.2)–(1.4), and (1.13)–(1.19) over the number of firms in the fossil-fuel industry for different values of b . The parameter b determines the extent to which a RES-E equipment firm can reduce its costs and marginal costs in the second period through learning in the first period. The results are illustrated in Figure A.1. For a low value of $b = 0.1$, the optimal subsidy for RES-E equipment producers decreases with an increasing number of fossil-fuel firms, whereas it increases for a relatively high value of $b = 0.8$.

A.3 Derivation of the strategic effect $\partial\tilde{y}_2/\partial y_1$

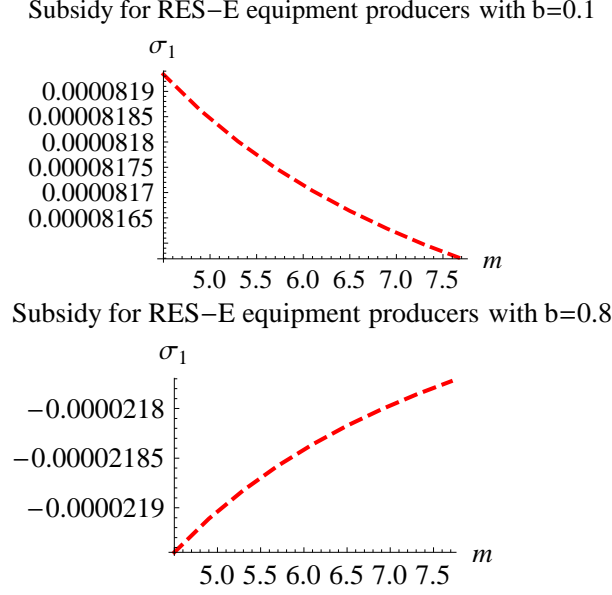


Figure A.1: The ambiguous effect of market structure in the fossil-fuel industry on the optimal learning subsidy rate.

A.3 Derivation of the strategic effect $\partial\tilde{y}_2/\partial y_1$

In order to analyze the effect of an output increase by one firm on any of the $(n-1)$ other firms (say, firms A and B), we set up the FOCs of both firms in the second period:

$$B_2(X_2) + B'_2(X_2)y_2 + \sigma_2 - \Gamma_{y_2}^2(y_2, L) = 0, \quad (\text{A.20})$$

$$B_2(X_2) + B'_2(X_2)\tilde{y}_2 + \sigma_2 - \Gamma_{\tilde{y}_2}^2(\tilde{y}_2, \tilde{L}) = 0, \quad (\text{A.21})$$

where y_2 and $L = y_1 + (n-1)\varepsilon\tilde{y}_2$ denote output and learning of firm A , and \tilde{y}_2 and $\tilde{L} = \tilde{y}_1 + (n-2)\varepsilon\tilde{y}_1 + \varepsilon y_1$ output and learning of firm B , respectively. The total number of RES-E equipment devices in the second period is given by $X_2 = y_2 + (n-1)\tilde{y}_2$. Differentiating (A.20) and (A.21) with respect to y_1 yields

A.4 Proof of the comparative-static effects of market concentration with oligopolistic competition in both the fossil-fuel and the RES-E equipment industry

the following system of equations:

$$[2B'_2(X_2) + B''_2(X_2)y_2 - \Gamma_{y_2y_2}^2(y_2, L)] \frac{\partial y_2}{\partial y_1} \quad (\text{A.22})$$

$$+ [B'_2(X_2) + B''_2(X_2)y_2](n-1) \frac{\partial \tilde{y}_2}{\partial y_1} - \Gamma_{y_2L}^2(y_2, L) = 0,$$

$$[B'_2(X_2) + B''_2(X_2)\tilde{y}_2] \frac{\partial y_2}{\partial y_1} \quad (\text{A.23})$$

$$+ [nB'_2(X_2) + (n-1)B''_2(X_2)\tilde{y}_2 - \Gamma_{\tilde{y}_2\tilde{y}_2}^2(\tilde{y}_2, \tilde{L})] \frac{\partial \tilde{y}_2}{\partial y_1} - \varepsilon \Gamma_{\tilde{y}_2\tilde{L}}^2(\tilde{y}_2, \tilde{L}) = 0.$$

Solving (A.23) and (A.24) for $\partial \tilde{y}_2 / \partial y_1$ and $\partial y_2 / \partial y_1$ we obtain the comparative-static effect of increasing output by firm A in period 1 on output of firm B in period 2:

$$\frac{\partial \tilde{y}_2}{\partial y_1} = \frac{\Gamma_{y_2L}^2(B'_2 + B''_2\tilde{y}_2) + \varepsilon[\Gamma_{\tilde{y}_2\tilde{L}}^2\Gamma_{y_2y_2}^2 - \Gamma_{\tilde{y}_2\tilde{L}}^2(2B'_2 + B''_2y_2)]}{D}, \quad (\text{A.24})$$

where

$$\begin{aligned} D = & -\Gamma_{\tilde{y}_2\tilde{y}_2}^2\Gamma_{y_2y_2}^2 - (n+1)(B'_2)^2 + \Gamma_{\tilde{y}_2\tilde{y}_2}^2(2B'_2 + B''_2y_2) \\ & + \Gamma_{y_2y_2}^2(nB'_2 + (n-1)B''_2\tilde{y}_2) - (y_2 + (n-1)\tilde{y}_2)B'_2B''_2. \end{aligned}$$

A.4 Proof of the comparative-static effects of market concentration with oligopolistic competition in both the fossil-fuel and the RES-E equipment industry

The proof of the comparative-static effects described in Section 1.4.2.1 essentially follows the same techniques as described in Appendix A.1, except that we use the inverse demand function for RES-E equipment, the first order conditions for RES-E equipment producers, and the optimal subsidy rates for the case of oligopolistic competition in the RES-E equipment industry given by (1.20) and (1.22) - (1.25), respectively. Differentiating the equations with respect to the number of firms in the RES-E equipment industry n leads to the following system of equations:

A.4 Proof of the comparative-static effects of market concentration with oligopolistic competition in both the fossil-fuel and the RES-E equipment industry

Aggregate electricity production:

$$\frac{\partial Q_1}{\partial n} = \frac{1}{1 - P'_1(Q_1)CC_1} \left[m \frac{\partial k_1}{\partial n} + q_1(X_1) \frac{\partial X_1}{\partial n} \right] \quad (\text{A.25})$$

$$\frac{\partial Q_2}{\partial n} = \frac{1}{1 - P'_2(Q_2)CC_2} \left[m \frac{\partial k_2}{\partial n} + q_2(X_2) \frac{\partial X_2}{\partial n} \right] \quad (\text{A.26})$$

Production of electricity by intra-marginal RES-E firms:

$$\frac{\partial q_1(\tilde{x})}{\partial n} = \frac{P'_1(Q_1)}{C_{qq}^1(q_1(\tilde{x}), \tilde{x})} \frac{\partial Q_1}{\partial n} \quad \forall \tilde{x} \leq X_1 \quad (\text{A.27})$$

$$\frac{\partial q_2(\tilde{x})}{\partial n} = \frac{P'_2(Q_2)}{C_{qq}^2(q_2(\tilde{x}), \tilde{x})} \frac{\partial Q_2}{\partial n} \quad \forall \tilde{x} \leq X_2 \quad (\text{A.28})$$

Production of electricity by fossil-fuel utilities:

$$0 = [P'_1(Q_1) + P''_1(Q_1)k_1] \frac{\partial Q_1}{\partial n} + [P'_1(Q_1) - K''_1(k_1)] \frac{\partial k_1}{\partial n} - \frac{\partial \tau_1}{\partial n} \quad (\text{A.29})$$

$$0 = [P'_2(Q_2) + P''_2(Q_2)k_2] \frac{\partial Q_2}{\partial n} + [P'_2(Q_2) - K''_2(k_2)] \frac{\partial k_2}{\partial n} - \frac{\partial \tau_2}{\partial n} \quad (\text{A.30})$$

Emission taxes:

$$\frac{\partial \tau_1}{\partial n} = P''_1(Q_1)k_1 \frac{\partial Q_1}{\partial n} + [P'_1(Q_1) + D''_1(mk_1)] \frac{\partial k_1}{\partial n} \quad (\text{A.31})$$

$$\frac{\partial \tau_2}{\partial n} = P''_2(Q_2)k_2 \frac{\partial Q_2}{\partial n} + [P'_2(Q_2) + D''_2(mk_2)] \frac{\partial k_2}{\partial n} \quad (\text{A.32})$$

Total number of RES-E equipment:

$$\frac{\partial X_1}{\partial n} = n \frac{\partial y_1}{\partial n} + y_1 \quad (\text{A.33})$$

$$\frac{\partial X_2}{\partial n} = n \frac{\partial y_2}{\partial n} + y_2 \quad (\text{A.34})$$

A.4 Proof of the comparative-static effects of market concentration with oligopolistic competition in both the fossil-fuel and the RES-E equipment industry

Electricity prices:

$$\frac{\partial p_1}{\partial n} = P'_1(Q_1) \frac{\partial Q_1}{\partial n} \quad (\text{A.35})$$

$$\frac{\partial p_2}{\partial n} = P'_2(Q_2) \frac{\partial Q_2}{\partial n} \quad (\text{A.36})$$

RES-E equipment prices:

$$\frac{\partial b_1}{\partial n} = P'_1(Q_1) q_1(X_1) \frac{\partial Q_1}{\partial n} - C'_X(q_1(X_1), X_1) \frac{\partial X_1}{\partial n} \quad (\text{A.37})$$

$$\frac{\partial b_2}{\partial n} = P'_2(Q_2) q_2(X_2) \frac{\partial Q_2}{\partial n} - C'_X(q_2(X_2), X_2) \frac{\partial X_2}{\partial n} \quad (\text{A.38})$$

Production of RES-E equipment firms:

$$0 = [B'_1(X_1) + B''_1(X_1)y_1] \frac{\partial X_1}{\partial n} \quad (\text{A.39})$$

$$+ [B'_1(X_1) - \Gamma^1_{y_1 y_1} - \delta \Gamma^2_{LL}(1 + (n-1)\varepsilon)] \frac{\partial y_1}{\partial n} + \frac{\partial \sigma_1}{\partial n}$$

$$+ \delta B''_2(X_2)(n-1) \frac{\partial \tilde{y}_2}{\partial y_1} \frac{\partial X_2}{\partial n} - \delta \Gamma^2_{y_2 L} \frac{\partial y_2}{\partial n} + \delta B'_2(X_2) \frac{\partial \tilde{y}_2}{\partial y_1} - \delta \Gamma^2_{LL} \varepsilon y_1$$

$$0 = [B'_2(X_2) + B''_2(X_2)y_2] \frac{\partial X_2}{\partial n} + [B'_2(X_2) - \Gamma^2_{y_2 y_2}] \frac{\partial y_2}{\partial n} + \frac{\partial \sigma_2}{\partial n} \quad (\text{A.40})$$

$$- \Gamma^2_{y_2 L}(1 + (n-1)\varepsilon) \frac{\partial y_1}{\partial n} - \Gamma^2_{y_2 L} \varepsilon y_1$$

Output subsidies for RES-E equipment firms:

$$\frac{\partial \sigma_1}{\partial n} = -[B'_1(X_1) + (n-1)\varepsilon \Gamma^2_{LL}(1 + (n-1)\varepsilon)] \frac{\partial y_1}{\partial n} - B''_1(X_1)y_1 \frac{\partial X_1}{\partial n} \quad (\text{A.41})$$

$$- \delta(n-1)\varepsilon \Gamma^2_{y_2 L} \frac{\partial y_2}{\partial n} - \delta B''_2(X_2)(n-1) \frac{\partial \tilde{y}_2}{\partial y_1} \frac{\partial X_2}{\partial n}$$

$$- \delta [B'_2(X_2) \frac{\partial \tilde{y}_2}{\partial y_1} + \varepsilon \Gamma^2_L + (n-1)\varepsilon^2 \Gamma^2_{LL} y_1]$$

$$\frac{\partial \sigma_2}{\partial n} = -B'_2(X_2) \frac{\partial y_2}{\partial n} - B''_2(X_2)y_2 \frac{\partial X_2}{\partial n} \quad (\text{A.42})$$

A.4 Proof of the comparative-static effects of market concentration with oligopolistic competition in both the fossil-fuel and the RES-E equipment industry

$B'_t(X_t)$ and $B''_t(X_t)$ are obtained by differentiating the zero-profit condition for RES-E producers given by equation 1.20 with respect to X_t , i.e.

$$B'_t(X_t) = \frac{P'_t(Q_t)q_t(X_t)^2}{1 - P'_t(Q_t)CC_t} - C_{Xt}^t(q_t(X_t), X_t) \quad (\text{A.43})$$

$$\begin{aligned} B''_t(X_t) &= \frac{P''_t(Q_t)q_t(X_t)^3}{[1 - P'_t(Q_t)CC_t]^2} - C_{XX}^t(q_t(X_t), X_t) \quad (\text{A.44}) \\ &+ \left[\frac{P'_t(Q_t)q_t(X_t)}{1 - P'_t(Q_t)CC_t} - C_{Xq}^t(q_t(X_t), X_t) \right] \left[\frac{P'_t(Q_t)q_t(X_t)}{C_{qq}^t(q_t(X_t), X_t)[1 - P'_t(Q_t)CC_t]} \right. \\ &- \left. \frac{C_{Xq}^t(q_t(X_t), X_t)}{C_{qq}^t(q_t(X_t), X_t)} \right] + P'_t(Q_t)q_t(X_t) \left[\frac{P'_t(Q_t)q_t(X_t)}{C_{qq}^t(q_t(X_t), X_t)[1 - P'_t(Q_t)CC_t]^2} \right. \\ &- \left. \frac{C_{Xq}^t(q_t(X_t), X_t)}{C_{qq}^t(q_t(X_t), X_t)[1 - P'_t(Q_t)CC_t]} + \frac{P'_t(Q_t)q_t(X_t)^2 CC_t}{[1 - P'_t(Q_t)CC_t]^2} \right]. \end{aligned}$$

To unambiguously sign the effects on the endogenous variables we impose two additional assumptions, again implying that the effects of learning on the marginal cost in the second period are not too large:

Condition 2 : $y_1 \Gamma_{Ly_2}^2 + y_2 \Gamma_{y_2 y_2}^2 \geq 0$,

Condition 3 : $\delta y_2 \Gamma_{Ly_2}^2 + y_1 (\Gamma_{y_1 y_1}^1 + \delta \Gamma_{LL}^2) \geq 0$.

Solving the system of equations for the comparative-static effects, assuming Conditions 1, 2 and 3 to hold yields the following results, where *Det* again denotes the determinant of the matrix:

**A.4 Proof of the comparative-static effects of market concentration
with oligopolistic competition in both the fossil-fuel and the RES-E
equipment industry**

$$\begin{aligned}
Det = & -C_{qq}^1 C_{qq}^2 \left\{ -(mD_1'' + K_1'') [-(mD_2'' + K_2'') ((C_X^1 n + \Gamma_{y_1 y_1}^1) (C_X^2 n + \Gamma_{y_2 y_2}^2)) \right. \\
& + \delta(C_X^2 n \Gamma_{LL}^2 + \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{y_2 L}^2)^2)}^{\text{Condition 1}})] + P_1' [-(m((C_X^1 n + \Gamma_{y_1 y_1}^1) (C_X^2 n + \Gamma_{y_2 y_2}^2)) \\
& + \delta(C_X^2 n \Gamma_{LL}^2 + \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{y_2 L}^2)^2)}^{\text{Condition 1}})) + ((CC_1 (C_X^1 n + \Gamma_{y_1 y_1}^1) + nq_1^2) (C_X^2 n + \Gamma_{y_2 y_2}^2) \\
& + CC_1 \delta(C_X^2 n \Gamma_{LL}^2 + \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{y_2 L}^2)^2)}^{\text{Condition 1}})) (mD_1'' + K_1'') \\
& + (mD_2'' + K_2'') P_2' [mD_2'' (m((C_X^1 n + \Gamma_{y_1 y_1}^1) (CC_2 (C_X^2 n + \Gamma_{y_2 y_2}^2) + nq_2^2) \\
& + \delta(CC_2 (\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{y_2 L}^2)^2}^{\text{Condition 1}}) + \Gamma_{LL}^2 (C_X^2 CC_2 n + nq_2^2))) \\
& + ((CC_1 (C_X^1 n + \Gamma_{y_1 y_1}^1) + nq_1^2) (CC_2 (C_X^2 n + \Gamma_{y_2 y_2}^2) + nq_2^2) + CC_1 \delta(CC_2 (\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{y_2 L}^2)^2}^{\text{Condition 1}}) \\
& + \Gamma_{LL}^2 (C_X^2 CC_2 n + nq_2^2))) K_1''] + m(m((C_X^1 n + \Gamma_{y_1 y_1}^1) (C_X^2 n + \Gamma_{y_2 y_2}^2) \\
& + \delta(C_X^2 n \Gamma_{LL}^2 + \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{y_2 L}^2)^2)}^{\text{Condition 1}})) + ((C_X^1 n + \Gamma_{y_1 y_1}^1) (CC_2 (C_X^2 n + \Gamma_{y_2 y_2}^2) + nq_2^2) \\
& + \delta(CC_2 (\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{y_2 L}^2)^2}^{\text{Condition 1}}) + \Gamma_{LL}^2 (C_X^2 CC_2 n + nq_2^2))) K_2''] \\
& + K_1'' (m((CC_1 (C_X^1 n + \Gamma_{y_1 y_1}^1) + nq_1^2) (C_X^2 n + \Gamma_{y_2 y_2}^2) + CC_1 \delta(C_X^2 n \Gamma_{LL}^2 + \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{y_2 L}^2)^2)}^{\text{Condition 1}})) \\
& + ((CC_1 (C_X^1 n + \Gamma_{y_1 y_1}^1) + nq_1^2) (CC_2 (C_X^2 n + \Gamma_{y_2 y_2}^2) + nq_2^2) + CC_1 \delta(CC_2 (\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{y_2 L}^2)^2}^{\text{Condition 1}}) \\
& + \Gamma_{LL}^2 (C_X^2 CC_2 n + nq_2^2))) K_2'') + mD_1'' (m((CC_1 (C_X^1 n + \Gamma_{y_1 y_1}^1) + nq_1^2) (C_X^2 n + \Gamma_{y_2 y_2}^2) \\
& + CC_1 \delta(C_X^2 n \Gamma_{LL}^2 + \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{y_2 L}^2)^2)}^{\text{Condition 1}})) + ((CC_1 (C_X^1 n + \Gamma_{y_1 y_1}^1) + nq_1^2) (CC_2 (C_X^2 n + \Gamma_{y_2 y_2}^2) \\
& + nq_2^2) + CC_1 \delta(CC_2 (\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{y_2 L}^2)^2}^{\text{Condition 1}}) + \Gamma_{LL}^2 (C_X^2 CC_2 n + nq_2^2))) (mD_2'' + K_2'')) \left. \right\} < 0
\end{aligned}$$

**A.4 Proof of the comparative-static effects of market concentration
with oligopolistic competition in both the fossil-fuel and the RES-E
equipment industry**

$$\begin{aligned}
 \frac{\partial k_1}{\partial n} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 q_1 P_1' \left\{ [\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}}] \right. \\
 &\quad [(mD_2'' + K_2'') y_1 (CC_2 P_2' - 1) + P_2' m y_1] + \overbrace{[\delta y_2 \Gamma_{Ly_2}^2 + y_1 (\Gamma_{y_1 y_1}^1 + \delta \Gamma_{LL}^2)]}^{\text{Condition 3}} \\
 &\quad \left. [(mD_2'' + K_2'') (C_X^2 n (P_2' CC_2 - 1) + P_2' n q_2^2) + P_2' C_X^2 n] \right\} < 0 \\
 \frac{\partial k_2}{\partial n} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 q_2 P_2' \left\{ [\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}}] \right. \\
 &\quad [(mD_1'' + K_1'') y_2 (CC_1 P_1' - 1) + P_1' m y_2] + \overbrace{(y_1 \Gamma_{Ly_2}^2 + y_2 \Gamma_{y_2 y_2}^2)}^{\text{Condition 2}} \\
 &\quad \left. [(mD_1'' + K_1'') (C_X^1 n (P_1' CC_1 - 1) + P_1' n q_1^2) + P_1' m C_X^1 n] \right\} < 0 \\
 \frac{\partial q_1}{\partial n} &= \frac{1}{Det} C_{qq}^2 q_1 P_1' (mD_1'' + K_1'') \left\{ [\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}}] \right. \\
 &\quad [(mD_2'' + K_2'') y_1 (CC_2 P_2' - 1) + P_2' m y_1] + \overbrace{[\delta y_2 \Gamma_{Ly_2}^2 + y_1 (\Gamma_{y_1 y_1}^1 + \delta \Gamma_{LL}^2)]}^{\text{Condition 3}} \\
 &\quad \left. [(mD_2'' + K_2'') (C_X^2 n (P_2' CC_2 - 1) + P_2' n q_2^2) + P_2' C_X^2 n] \right\} < 0 \\
 \frac{\partial q_2}{\partial n} &= \frac{1}{Det} C_{qq}^1 q_2 P_2' (mD_2'' + K_2'') \left\{ [\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}}] \right. \\
 &\quad [(mD_1'' + K_1'') y_2 (CC_1 P_1' - 1) + P_1' m y_2] + \overbrace{(y_1 \Gamma_{Ly_2}^2 + y_2 \Gamma_{y_2 y_2}^2)}^{\text{Condition 2}} \\
 &\quad \left. [(mD_1'' + K_1'') (C_X^1 n (P_1' CC_1 - 1) + P_1' n q_1^2) + P_1' m C_X^1 n] \right\} < 0 \\
 \frac{\partial Q_1}{\partial n} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 q_1 (mD_1'' + K_1'') \left\{ [\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}}] \right. \\
 &\quad [(mD_2'' + K_2'') y_1 (CC_2 P_2' - 1) + P_2' m y_1] + \overbrace{[\delta y_2 \Gamma_{Ly_2}^2 + y_1 (\Gamma_{y_1 y_1}^1 + \delta \Gamma_{LL}^2)]}^{\text{Condition 3}} \\
 &\quad \left. [(mD_2'' + K_2'') (C_X^2 n (P_2' CC_2 - 1) + P_2' n q_2^2) + P_2' C_X^2 n] \right\} > 0 \\
 \frac{\partial Q_2}{\partial n} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 q_2 (mD_2'' + K_2'') \left\{ [\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}}] \right. \\
 &\quad [(mD_1'' + K_1'') y_2 (CC_1 P_1' - 1) + P_1' m y_2] + \overbrace{(y_1 \Gamma_{Ly_2}^2 + y_2 \Gamma_{y_2 y_2}^2)}^{\text{Condition 2}} \\
 &\quad \left. [(mD_1'' + K_1'') (C_X^1 n (P_1' CC_1 - 1) + P_1' n q_1^2) + P_1' m C_X^1 n] \right\} > 0
 \end{aligned}$$

**A.4 Proof of the comparative-static effects of market concentration
with oligopolistic competition in both the fossil-fuel and the RES-E
equipment industry**

$$\begin{aligned}
\frac{\partial X_1}{\partial n} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 ((mD_1'' + K_1'')(1 - P_1'CC_1) - P_1'm) \\
&\quad \{[\Gamma_{y_1y_1}^1 \Gamma_{y_2y_2}^2 + \delta \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}}]\} \\
&\quad [(mD_2'' + K_2'')y_1(CC_2P_2' - 1) + P_2'my_1] + \overbrace{[\delta y_2 \Gamma_{Ly_2}^2 + y_1(\Gamma_{y_1y_1}^1 + \delta \Gamma_{LL}^2)]}^{\text{Condition 3}} \\
&\quad [(mD_2'' + K_2'')(C_X^2 n(P_2'CC_2 - 1) + P_2'nq_2^2) + P_2'C_X^2 n] \} < 0 \\
\frac{\partial X_2}{\partial n} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 ((mD_2'' + K_2'')(1 - P_2'CC_2) - P_2'm) \\
&\quad \{[\Gamma_{y_1y_1}^1 \Gamma_{y_2y_2}^2 + \delta \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}}]\} \\
&\quad [(mD_1'' + K_1'')y_2(CC_1P_1' - 1) + P_1'my_2] + \overbrace{(y_1 \Gamma_{Ly_2}^2 + y_2 \Gamma_{y_2y_2}^2)}^{\text{Condition 2}} \\
&\quad [(mD_1'' + K_1'')(C_X^1 n(P_1'CC_1 - 1) + P_1'nq_1^2) + P_1'mC_X^1 n] \} < 0 \\
\frac{\partial b_1}{\partial n} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 [(mD_1'' + K_1'')(P_1'(C_X^1 m + C_X^1 CC_1 + q_1^2) - C_X^1)] \\
&\quad \{[\Gamma_{y_1y_1}^1 \Gamma_{y_2y_2}^2 + \delta \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}}]\} \\
&\quad [(mD_2'' + K_2'')y_1(CC_2P_2' - 1) + P_2'my_1] + \overbrace{[\delta y_2 \Gamma_{Ly_2}^2 + y_1(\Gamma_{y_1y_1}^1 + \delta \Gamma_{LL}^2)]}^{\text{Condition 3}} \\
&\quad [(mD_2'' + K_2'')(C_X^2 n(P_2'CC_2 - 1) + P_2'nq_2^2) + P_2'C_X^2 n] \} < 0 \\
\frac{\partial b_2}{\partial n} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 [(mD_2'' + K_2'')(P_2'(C_X^2 m + C_X^2 CC_2 + q_2^2) - C_X^2)] \\
&\quad + \{[\Gamma_{y_1y_1}^1 \Gamma_{y_2y_2}^2 + \delta \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}}]\} [(mD_1'' + K_1'')y_2(CC_1P_1' - 1) + P_1'my_2] \\
&\quad + \overbrace{(y_1 \Gamma_{Ly_2}^2 + y_2 \Gamma_{y_2y_2}^2)}^{\text{Condition 2}} [(mD_1'' + K_1'')(C_X^1 n(P_1'CC_1 - 1) + P_1'nq_1^2) + P_1'mC_X^1 n] \} < 0 \\
\frac{\partial \tau_1}{\partial n} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 q_2 [(P_1')^2 + mP_1'D_1'' + k_1P_1''(mD_1'' + K_1'')] \\
&\quad \{[\Gamma_{y_1y_1}^1 \Gamma_{y_2y_2}^2 + \delta \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}}]\} [(mD_2'' + K_2'')y_1(CC_2P_2' - 1) + P_2'my_1] \\
&\quad + \overbrace{[\delta y_2 \Gamma_{Ly_2}^2 + y_1(\Gamma_{y_1y_1}^1 + \delta \Gamma_{LL}^2)]}^{\text{Condition 3}} [(mD_2'' + K_2'')(C_X^2 n(P_2'CC_2 - 1) + P_2'nq_2^2) + P_2'C_X^2 n] \} < 0
\end{aligned}$$

A.4 Proof of the comparative-static effects of market concentration with oligopolistic competition in both the fossil-fuel and the RES-E equipment industry

$$\begin{aligned} \frac{\partial \tau_2}{\partial n} &= \frac{1}{\text{Det}} C_{qq}^1 C_{qq}^2 q_2 [(P_2')^2 + m P_2' D_2'' + k_2 P_2'' (m D_2'' + K_2'')] \\ &\quad \{ [\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}}] [(m D_1'' + K_1'') y_2 (C C_1 P_1' - 1) + P_1' m y_2] \\ &\quad + \overbrace{(y_1 \Gamma_{Ly_2}^2 + y_2 \Gamma_{y_2 y_2}^2)}^{\text{Condition 2}} [(m D_1'' + K_1'') (C_X^1 n (P_1' C C_1 - 1) + P_1' n q_1^2) + P_1' m C_X^1 n] \} < 0 \end{aligned}$$

The signs of the variation of the subsidy rates cannot be determined without further assumptions. Simplifying the expressions for the subsidy rates with $\Gamma_{LL}^2 \approx 0$ and $\Gamma_{Ly_2}^2 \approx 0$ yields the following results:

$$\begin{aligned} \frac{\partial \sigma_1}{\partial n} &= \frac{1}{\text{Det}(P_1' C C_1 - 1)^2} \\ &\quad [(C_X^2 n + \Gamma_{y_2 y_2}^2) ((m D_2'' + K_2'') (P_2' C C_2 - 1) + P_2' m) + P_2' n q_2^2 (m D_2'' + K_2'')] \\ &\quad \{ P_1' [C_{qq}^1 m ((C_X^1)^2 - C_{XX}^1 y_1 \Gamma_{y_1 y_1}^1) + (C_{qq}^1 C_X^1 (3 C_X^1 C C_1 + 2 q_1^2) \\ &\quad + (-3 C_{qq}^1 C_X^1 C C_1 + C_{qX}^1 q_1) y_1 \Gamma_{y_1 y_1}^1) (m D_1'' + K_1'')] \\ &\quad - (P_1')^2 [C_{qq}^1 m (C_X^1 (2 C_X^1 C C_1 + q_1^2) - 2 C_{XX}^1 C C_1 y_1 \Gamma_{y_1 y_1}^1) + (2 q_1 (C_{qX}^1 C C_1 + q_1) y_1 \Gamma_{y_1 y_1}^1 \\ &\quad + C_{qq}^1 (3 (C_X^1 C C_1)^2 + 4 C_X^1 C C_1 q_1^2 + q_1^4 - 3 C_{XX}^1 (C C_1)^2 y_1 \Gamma_{y_1 y_1}^1)) (m D_1'' + K_1'')] \\ &\quad + C C_1 (P_1')^3 [C_{qq}^1 m (C_X^1 (C_X^1 C C_1 + q_1^2) - C_{XX}^1 C C_1 y_1 \Gamma_{y_1 y_1}^1) + (q_1 (C_{qX}^1 C C_1 + 2 q_1) y_1 \Gamma_{y_1 y_1}^1 \\ &\quad + C_{qq}^1 ((C_X^1 C C_1 + q_1^2)^2 - C_{XX}^1 (C C_1)^2 y_1 \Gamma_{y_1 y_1}^1)) \\ &\quad (m D_1'' + K_1'')] - C_{qq}^1 (m D_1'' + K_1'') ((C_X^1)^2 - C_{XX}^1 y_1 \Gamma_{y_1 y_1}^1 + q_1^3 y_1 \Gamma_{y_1 y_1}^1 P_1'') \} < 0 \\ \frac{\partial \sigma_2}{\partial n} &= \frac{1}{\text{Det}(P_2' C C_2 - 1)^2} \\ &\quad [(C_X^1 n + \Gamma_{y_1 y_1}^1) ((m D_1'' + K_1'') (P_1' C C_1 - 1) + P_1' m) + P_1' n q_1^2 (m D_1'' + K_1'')] \\ &\quad \{ P_2' [C_{qq}^2 m ((C_X^2)^2 - C_{XX}^2 y_2 \Gamma_{y_2 y_2}^2) + (C_{qq}^2 C_X^2 (3 C_X^2 C C_2 + 2 q_2^2) \\ &\quad + (-3 C_{qq}^2 C_X^2 C C_2 + C_{qX}^2 q_2) y_2 \Gamma_{y_2 y_2}^2) (m D_2'' + K_2'')] \\ &\quad - (P_2')^2 [C_{qq}^2 m (C_X^2 (2 C_X^2 C C_2 + q_2^2) - 2 C_{XX}^2 C C_2 y_2 \Gamma_{y_2 y_2}^2) + (2 q_2 (C_{qX}^2 C C_2 + q_2) y_2 \Gamma_{y_2 y_2}^2 \\ &\quad + C_{qq}^2 (3 (C_X^2 C C_2)^2 + 4 C_X^2 C C_2 q_2^2 + q_2^4 - 3 C_{XX}^2 (C C_2)^2 y_2 \Gamma_{y_2 y_2}^2)) (m D_2'' + K_2'')] \\ &\quad + C C_2 (P_2')^3 [C_{qq}^2 m (C_X^2 (C_X^2 C C_2 + q_2^2) - C_{XX}^2 C C_2 y_2 \Gamma_{y_2 y_2}^2) + (q_2 (C_{qX}^2 C C_2 + 2 q_2) y_2 \Gamma_{y_2 y_2}^2 \\ &\quad + C_{qq}^2 ((C_X^2 C C_2 + q_2^2)^2 - C_{XX}^2 (C C_2)^2 y_2 \Gamma_{y_2 y_2}^2)) (m D_2'' + K_2'')] \\ &\quad - C_{qq}^2 (m D_2'' + K_2'') ((C_X^2)^2 - C_{XX}^2 y_2 \Gamma_{y_2 y_2}^2 + q_2^3 y_2 \Gamma_{y_2 y_2}^2 P_2'') \} < 0 \end{aligned}$$

A.4 Proof of the comparative-static effects of market concentration with oligopolistic competition in both the fossil-fuel and the RES-E equipment industry

Similarly, differentiating the system of equations with respect to the number of firms in the fossil fuel industry m yields the following comparative-static results:

$$\begin{aligned}
\frac{\partial q_1}{\partial m} &= \frac{1}{Det} C_{qq}^2 P_1' \{ -k_1 K_1'' (m D_2'' + K_2'') ((C_X^1 n + \Gamma_{y_1 y_1}^1) \delta(C_X^2 n + \Gamma_{y_2 y_2}^2) \\
&\quad + \delta(C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}})) + P_2' [k_2 m n q_1 q_2 \delta \Gamma_{y_2 L}^2 D_1'' K_2'' \\
&\quad + K_1'' [k_1 m ((C_X^1 n + \Gamma_{y_1 y_1}^1) \delta(C_X^2 n + \Gamma_{y_2 y_2}^2) + \delta(C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}})) \\
&\quad + k_1 m D_2'' ((C_X^1 n + \Gamma_{y_1 y_1}^1) (CC_2 (C_X^2 n + \Gamma_{y_2 y_2}^2) + n q_2^2) + \delta(\Gamma_{LL}^2 (C_X^2 n CC_2 + n q_2^2) \\
&\quad + \overbrace{CC_2 (\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}})] + K_2'' [k_1 (C_X^1 n + \Gamma_{y_1 y_1}^1) (CC_2 (C_X^2 n + \Gamma_{y_2 y_2}^2) + n q_2^2) \\
&\quad + \delta(C_X^2 CC_2 k_1 n \Gamma_{LL}^2 + k_2 n q_1 q_2 \Gamma_{y_2 L}^2 + k_1 (n q_2^2 \Gamma_{LL}^2 + CC_2 (\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}})))] \} < 0 \\
\frac{\partial q_2}{\partial m} &= \frac{1}{Det} C_{qq}^1 P_2' \{ -k_2 K_2'' (m D_1'' + K_1'') K_2'' ((C_X^1 n + \Gamma_{y_1 y_1}^1) (C_X^2 n + \Gamma_{y_2 y_2}^2) \\
&\quad + \delta(C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}})) + P_1' [k_1 m n q_1 q_2 \Gamma_{y_2 L}^2 D_2'' K_1'' \\
&\quad + K_2'' [k_2 m ((C_X^1 n + \Gamma_{y_1 y_1}^1) (C_X^2 n + \Gamma_{y_2 y_2}^2) + \delta(C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}})) \\
&\quad + k_2 m D_1'' ((C_X^2 n + \Gamma_{y_2 y_2}^2) (CC_1 (C_X^1 n + \Gamma_{y_1 y_1}^1) + n q_1^2) \\
&\quad + \delta CC_1 (\Gamma_{LL}^2 C_X^2 n + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}})] \\
&\quad + K_1'' [k_1 n q_1 q_2 \Gamma_{Ly_2}^2 + C_X^1 CC_1 k_2 n (C_X^2 n + \Gamma_{y_2 y_2}^2) + C_X^2 k_2 n (n q_1^2 + CC_1 (\Gamma_{y_1 y_1}^1 + \delta \Gamma_{LL}^2)) \\
&\quad + k_2 (n q_1^2 \Gamma_{y_2 y_2}^2 + CC_1 (\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta (\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}})))] \} < 0
\end{aligned}$$

**A.4 Proof of the comparative-static effects of market concentration
with oligopolistic competition in both the fossil-fuel and the RES-E
equipment industry**

$$\begin{aligned}
\frac{\partial k_1}{\partial m} = & \frac{1}{Det} C_{qq}^1 C_{qq}^2 \{ -k_1 D_1'' [-((C_X^1 n + \Gamma_{y_1 y_1}^1)(C_X^2 n + \Gamma_{y_2 y_2}^2)) \\
& + \delta(C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{Condition\ 1}) (m D_2'' + K_2'') \\
& + P_2' [m(C_X^1 n + \Gamma_{y_1 y_1}^1)(C_X^2 n + \Gamma_{y_2 y_2}^2) + m \delta(C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{Condition\ 1}) \\
& + (m D_2'' + K_2'') + [(C_X^1 n + \Gamma_{y_1 y_1}^1)(C C_2(C_X^2 n + \Gamma_{y_2 y_2}^2 + n q_2^2)) \\
& + \delta(\Gamma_{LL}^2(C_X^2 n C C_2 + n q_2^2) + C C_2(\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{Condition\ 1}))]] \\
& + P_1' [-k_1 (m D_2'' + K_2'') [(C_X^1 n + \Gamma_{y_1 y_1}^1)(C_X^2 n + \Gamma_{y_2 y_2}^2) + \delta(C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{Condition\ 1}) \\
& + D_1'' ((C C_1(C_X^1 n + \Gamma_{y_1 y_1}^1) + n q_1^2)(C_X^2 n + \Gamma_{y_2 y_2}^2) \\
& + \delta C C_1(C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{Condition\ 1}))] \\
& + P_2' [k_1 m ((C_X^1 n + \Gamma_{y_1 y_1}^1)(C_X^2 n + \Gamma_{y_2 y_2}^2) + \delta(C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{Condition\ 1})) \\
& + k_1 m D_2'' [(C_X^1 n + \Gamma_{y_1 y_1}^1)(C C_2(C_X^2 n + \Gamma_{y_2 y_2}^2 + n q_2^2)) + \delta(\Gamma_{LL}^2(C_X^2 n C C_2 + n q_2^2) \\
& + C C_2(\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{Condition\ 1}))] + K_2'' [k_1 (C_X^1 n + \Gamma_{y_1 y_1}^1)(C C_2(C_X^2 n + \Gamma_{y_2 y_2}^2 + n q_2^2)) \\
& + \delta(C_X^2 n C C_2 k_1 \Gamma_{LL}^2 + k_2 n q_2 q_1 \Gamma_{Ly_2}^2 + k_1 (n q_2^2 \Gamma_{LL}^2 + C C_2(\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{Condition\ 1})))] \\
& + k_1 D_1'' [m (C C_1(C_X^1 n + \Gamma_{y_1 y_1}^1) + n q_1^2)(C_X^2 n + \Gamma_{y_2 y_2}^2) \\
& + C C_1 m \delta(C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{Condition\ 1}) \\
& + (m D_2'' + K_2'') [(C C_1(C_X^1 n + \Gamma_{y_1 y_1}^1) + n q_1^2)(C C_2(C_X^2 n + \Gamma_{y_2 y_2}^2 + n q_2^2)) \\
& + C C_1 \delta(\Gamma_{LL}^2(C_X^2 n C C_2 + n q_2^2) + C C_2(\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{Condition\ 1}))]] \} < 0
\end{aligned}$$

**A.4 Proof of the comparative-static effects of market concentration
with oligopolistic competition in both the fossil-fuel and the RES-E
equipment industry**

$$\begin{aligned}
\frac{\partial k_2}{\partial m} = & \frac{1}{Det} C_{qq}^1 C_{qq}^2 \{ -k_2 (mD_1'' + K_1'') [-D_2'' ((C_X^1 n + \Gamma_{y_1 y_1}^1) (C_X^2 n + \Gamma_{y_2 y_2}^2)) \\
& + \delta (C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}}) + P_2' [(C_X^1 n + \Gamma_{y_1 y_1}^1) (C_X^2 n + \Gamma_{y_2 y_2}^2)] \\
& + \delta (C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}}) + (mD_2'' + K_2'') + D_2'' [(C_X^1 n + \Gamma_{y_1 y_1}^1) \\
& (CC_2 (C_X^2 n + \Gamma_{y_2 y_2}^2 + nq_2^2)) + \delta (\Gamma_{LL}^2 (C_X^2 n CC_2 + nq_2^2) + CC_2 \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}})]]] \\
& + P_1' [-k_2 D_2'' [m (C_X^1 n + \Gamma_{y_1 y_1}^1) (C_X^2 n + \Gamma_{y_2 y_2}^2) + m \delta (C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}}) \\
& + (mD_1'' + K_1'') ((CC_1 (C_X^1 n + \Gamma_{y_1 y_1}^1) + nq_1^2) (C_X^2 n + \Gamma_{y_2 y_2}^2) \\
& + \delta CC_1 (C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}})] + P_2' [k_2 m ((C_X^1 n + \Gamma_{y_1 y_1}^1) (C_X^2 n + \Gamma_{y_2 y_2}^2) \\
& + \delta (C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}}) + k_2 m D_1'' [(C_X^2 n + \Gamma_{y_2 y_2}^2) (CC_1 (C_X^1 n + \Gamma_{y_1 y_1}^1 + nq_1^2)) \\
& + \delta CC_1 (C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}}) + D_2'' [(CC_1 (C_X^1 n + \Gamma_{y_1 y_1}^1) + nq_1^2) \\
& (CC_2 (C_X^2 n + \Gamma_{y_2 y_2}^2 + nq_2^2)) + \delta CC_1 (\Gamma_{LL}^2 (C_X^2 n CC_2 + nq_2^2) + CC_2 \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}})]] \\
& + K_1'' [k_1 n q_1 q_2 \Gamma_{Ly_2}^2 + C_X^1 CC_1 k_2 n (C_X^2 n + \Gamma_{y_2 y_2}^2) + C_X^2 k_2 n (CC_1 (\Gamma_{y_1 y_1}^1 + \delta \Gamma_{LL}^2) + nq_1^2) \\
& + k_2 (nq_1^2 \Gamma_{y_2 y_2}^2 + CC_1 (\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}})] \\
& + k_2 D_2'' [m (C_X^1 n + \Gamma_{y_1 y_1}^1) (C_X^2 n + \Gamma_{y_2 y_2}^2) + m \delta (\Gamma_{LL}^2 (C_X^2 n CC_2 + nq_2^2) \\
& + \overbrace{CC_2 (\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}}) + K_1'' [(CC_1 (C_X^1 n + \Gamma_{y_1 y_1}^1) + nq_1^2) (CC_2 (C_X^2 n + \Gamma_{y_2 y_2}^2 + nq_2^2)) \\
& + CC_1 \delta (\Gamma_{LL}^2 (C_X^2 n CC_2 + nq_2^2) + CC_2 \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{\text{Condition 1}})]]] \} < 0
\end{aligned}$$

**A.4 Proof of the comparative-static effects of market concentration
with oligopolistic competition in both the fossil-fuel and the RES-E
equipment industry**

$$\begin{aligned}
\frac{\partial X_1}{\partial m} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 n \{ k_2 q_2 \delta \Gamma_{Ly_2}^2 P_2' K_2'' (m D_1'' + K_1'') \\
&\quad + P_1' [-k_1 q_1 (C_X^2 n + \Gamma_{y_2 y_2}^2) K_1'' (m D_2'' + K_2'') \\
&\quad + P_2' [k_2 m q_2 \delta \Gamma_{Ly_2}^2 (1 + P_1' C C_1) K_2'' + K_1'' [k_1 m q_1 (C_X^2 n + \Gamma_{y_2 y_2}^2) \\
&\quad + k_1 m q_1 D_2'' (C C_2 (C_X^2 n + \Gamma_{y_2 y_2}^2) + n q_2^2) \\
&\quad + K_2'' [k_1 q_1 (C C_2 (C_X^2 n + \Gamma_{y_2 y_2}^2) - C C_1 k_2 q_2 \delta \Gamma_{Ly_2}^2)]]] \} < 0 \\
\frac{\partial X_2}{\partial m} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 n \{ -k_2 q_2 P_2' K_2'' (m D_1'' + K_1'') (C_X^1 n + \Gamma_{y_1 y_1}^1 + \delta \Gamma_{LL}^2) \\
&\quad + P_1' [k_1 q_1 \Gamma_{Ly_2}^2 K_1'' (m D_2'' + K_2'') \\
&\quad + P_2' [k_2 m q_2 K_2'' (C_X^1 n + \Gamma_{y_1 y_1}^1 + \delta \Gamma_{LL}^2) + D_1'' (C C_1 (C_X^1 n + \Gamma_{y_1 y_1}^1 + \delta \Gamma_{LL}^2) + n q_1^2) \\
&\quad + K_1'' [-\Gamma_{Ly_2}^2 k_1 m q_1 (1 + C C_1 D_2'') + K_2'' (C_X^1 n C C_1 k_2 q_2 - C C_2 k_1 q_1 \Gamma_{Ly_2}^2 \\
&\quad + k_2 q_2 (C C_1 (\Gamma_{y_1 y_1}^1 + \delta \Gamma_{LL}^2) + n q_1^2))] \} < 0 \\
\frac{\partial Q_1}{\partial m} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 \{ -k_1 K_1'' (m D_2'' + K_2'') ((C_X^1 n + \Gamma_{y_1 y_1}^1) (C_X^2 n + \Gamma_{y_2 y_2}^2) \\
&\quad + \delta (C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{Condition\ 1}) + P_2' [k_2 m n q_1 q_2 \delta \Gamma_{Ly_2}^2 D_1'' K_2'' \\
&\quad + K_1'' [k_1 m ((C_X^1 n + \Gamma_{y_1 y_1}^1) (C_X^2 n + \Gamma_{y_2 y_2}^2) + \delta (C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{Condition\ 1}) \\
&\quad + k_1 m D_2'' [(C_X^1 n + \Gamma_{y_1 y_1}^1) (C C_2 (C_X^2 n + \Gamma_{y_2 y_2}^2) + n q_2^2) + \delta (\Gamma_{LL}^2 (C_X^2 n C C_2 + n q_2^2) \\
&\quad + C C_2 (\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{Condition\ 1})] + K_2'' [k_1 (C_X^1 n + \Gamma_{y_1 y_1}^1) (C C_2 (C_X^2 n + \Gamma_{y_2 y_2}^2) + n q_2^2) \\
&\quad + \delta (k_1 n \Gamma_{LL}^2 (C_X^2 C C_2 + q_2^2) + k_2 n q_1 q_2 \Gamma_{Ly_2}^2 + k_1 C C_2 (\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{Condition\ 1})] \} > 0
\end{aligned}$$

**A.4 Proof of the comparative-static effects of market concentration
with oligopolistic competition in both the fossil-fuel and the RES-E
equipment industry**

$$\begin{aligned}
\frac{\partial Q_2}{\partial m} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 \{ -k_2 K_2'' (m D_1'' + K_1'') ((C_X^1 n + \Gamma_{y_1 y_1}^1) (C_X^2 n + \Gamma_{y_2 y_2}^2)) \\
&\quad + \delta (C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}}) + P_1' [k_1 m n q_1 q_2 \Gamma_{Ly_2}^2 D_2'' K_1'' \\
&\quad + K_2'' [k_2 m ((C_X^1 n + \Gamma_{y_1 y_1}^1) (C_X^2 n + \Gamma_{y_2 y_2}^2) + \delta (C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}})) \\
&\quad + k_2 m D_1'' ((C_X^2 n + \Gamma_{y_2 y_2}^2) (C C_1 (C_X^1 n + \Gamma_{y_1 y_1}^1) + n q_1^2) \\
&\quad + \delta C C_1 (C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}})] \\
&\quad + K_1'' [k_1 n q_1 q_2 \Gamma_{Ly_2}^2 + C_X^1 C C_1 k_2 n (C_X^2 n + \Gamma_{y_2 y_2}^2) + C_X^2 k_2 n (C C_1 (\Gamma_{y_1 y_1}^1 + \delta \Gamma_{LL}^2) + n q_1^2) \\
&\quad + k_2 (\Gamma_{y_2 y_2}^2 (n q_1^2 + C C_1 \Gamma_{y_1 y_1}^1) + \delta (\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}}))] \} > 0 \\
\frac{\partial b_1}{\partial m} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 \{ -C_X^1 k_2 n q_2 \delta \Gamma_{Ly_2}^2 P_2' (m D_1'' + K_1'') K_2'' + P_1' [-k_1 q_1 K_1'' (m D_2'' + K_2'') \\
&\quad (\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta (\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}}) + C_X^2 n (\Gamma_{y_1 y_1}^1 + \delta \Gamma_{LL}^2)) \\
&\quad + P_2' [k_2 m n q_2 \delta \Gamma_{Ly_2}^2 K_2'' (C_X^1 + D_1'' (C_X^1 C C_1 + q_1^2)) + K_1'' [k_1 m q_1 (\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 \\
&\quad + \delta (\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}})) + k_1 m q_1 D_2'' ((C_X^2 n C C_2 + n q_2^2) (\Gamma_{y_1 y_1}^1 + \delta \Gamma_{LL}^2) \\
&\quad + C C_2 (\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta (\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}}))] + K_2'' [k_2 n q_2 \delta \Gamma_{Ly_2}^2 (C_X^1 C C_1 + q_1^2) \\
&\quad + C_X^2 C C_2 k_1 n q_1 (\Gamma_{y_1 y_1}^1 + \delta \Gamma_{LL}^2) + k_1 q_1 (n q_2^2 (\Gamma_{y_1 y_1}^1 + \delta \Gamma_{LL}^2) + C C_2 (\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 \\
&\quad + \delta (\overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2}^{\text{Condition 1}}))] \} < 0
\end{aligned}$$

**A.4 Proof of the comparative-static effects of market concentration
with oligopolistic competition in both the fossil-fuel and the RES-E
equipment industry**

$$\begin{aligned}
\frac{\partial b_2}{\partial m} = & \frac{1}{Det} C_{qq}^1 C_{qq}^2 \{ -k_2 q_2 P_2' K_2'' (m D_1'' + K_1'') \\
& (\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + C_X^1 n \Gamma_{y_2 y_2}^2 + \delta \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{Condition\ 1}) \\
& + P_1' [-C_X^2 k_1 n q_1 \Gamma_{Ly_2}^2 K_1'' (m D_2'' + K_2'') + P_2' [k_2 m q_2 K_2'' [\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + C_X^1 n \Gamma_{y_2 y_2}^2 \\
& + \delta \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{Condition\ 1}] + D_1'' (\Gamma_{y_2 y_2}^2 n (C_X^1 C C_1 + n q_1^2) \\
& + C C_1 (\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{Condition\ 1})))] \\
& + K_1'' [k_1 m n q_1 \Gamma_{Ly_2}^2 (C_X^2 + D_2'' (C_X^2 C C_2 + q_2^2)) + K_2'' [k_1 n q_1 \Gamma_{Ly_2}^2 C_X^2 C C_2 + q_2 (k_1 n q_1 q_2 \Gamma_{Ly_2}^2 \\
& + k_2 (\Gamma_{y_2 y_2}^2 n (C_X^1 C C_1 + n q_1^2) + C C_1 (\Gamma_{y_1 y_1}^1 \Gamma_{y_2 y_2}^2 + \delta \overbrace{(\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)}^{Condition\ 1})))]] \} < 0
\end{aligned}$$

Again, the signs of the variation of the tax and subsidy rates cannot be determined without further assumptions. Simplifying the expressions for the tax and subsidy rates with $\Gamma_{LL}^2 \approx 0$ and $\Gamma_{Ly_2}^2 \approx 0$ yields the following results:

$$\begin{aligned}
\frac{\partial \tau_1}{\partial m} = & \frac{1}{Det} C_{qq}^1 C_{qq}^2 k_1 [- (C_X^2 n + \Gamma_{y_2 y_2}^2) (m D_2'' + K_2'') + P_2' (m (C_X^2 n + \Gamma_{y_2 y_2}^2) \\
& + (C C_2 (C_X^2 n + \Gamma_{y_2 y_2}^2) + n q_2^2) (m D_2'' + K_2''))] [(P_1')^2 (C_X^1 n + \Gamma_{y_1 y_1}^1 \\
& + (C C_1 (C_X^1 n + \Gamma_{y_1 y_1}^1) + n q_1^2) D_1'') - P_1' D_1'' (C_X^1 n + \Gamma_{y_1 y_1}^1 \\
& + (C C_1 (C_X^1 n + \Gamma_{y_1 y_1}^1) + n q_1^2) K_1'') + (C_X^1 n + \Gamma_{y_1 y_1}^1) K_1'' (D_1'' + P_1'' k_1)] < 0 \\
\frac{\partial \tau_2}{\partial m} = & \frac{1}{Det} C_{qq}^1 C_{qq}^2 k_2 [- (C_X^1 n + \Gamma_{y_1 y_1}^1) (m D_1'' + K_1'') + P_1' (m (C_X^1 n + \Gamma_{y_1 y_1}^1) \\
& + (C C_1 (C_X^1 n + \Gamma_{y_1 y_1}^1) + n q_1^2) (m D_1'' + K_1''))] [(P_2')^2 (C_X^2 n + \Gamma_{y_2 y_2}^2 \\
& + (C C_2 (C_X^2 n + \Gamma_{y_2 y_2}^2) + n q_2^2) D_2'') - P_2' D_2'' (C_X^2 n + \Gamma_{y_2 y_2}^2 \\
& + (C C_2 (C_X^2 n + \Gamma_{y_2 y_2}^2) + n q_2^2) K_2'') + (C_X^2 n + \Gamma_{y_2 y_2}^2) K_2'' (D_2'' + P_2'' k_2)] < 0
\end{aligned}$$

$$\begin{aligned}
\frac{\partial \sigma_1}{\partial m} &= -\frac{1}{\text{Det}(CC_1P'_1 - 1)^2} C_{qq}^2 K_1'' k_1 [-(C_X^2 n + \Gamma_{y_2 y_2}^2)(mD_2'' + K_2'') + P'_2(m(C_X^2 n + \Gamma_{y_2 y_2}^2) \\
&\quad + (CC_2(C_X^2 n + \Gamma_{y_2 y_2}^2) + nq_2^2)(mD_2'' + K_2''))][-P'_1(C_{qq}^1 q_1(C_X^1 + C_{X X}^1 n y_1) \\
&\quad + C_{qX}^1 y_1(C_X^1 n + \Gamma_{y_1 y_1}^1)) + (P'_1)^2(C_{qq}^1 q_1(q_1^2 + 2CC_1(C_X^1 + C_{X X}^1 n y_1)) \\
&\quad + 2y_1(C_{qX}^1 CC_1 + q_1)(C_X^1 n + \Gamma_{y_1 y_1}^1)) - (P'_1)^3 CC_1(C_{qq}^1 q_1(q_1^2 + CC_1 C_X^1 + C_{X X}^1 CC_1 n y_1) \\
&\quad + y_1(C_{qX}^1 CC_1 + 2q_1)(C_X^1 n + \Gamma_{y_1 y_1}^1)) + C_{qq}^1 q_1^2 y_1 P'_1(C_X^1 n + \Gamma_{y_1 y_1}^1)] > 0 \\
\frac{\partial \sigma_2}{\partial m} &= -\frac{1}{\text{Det}(CC_2P'_2 - 1)^2} C_{qq}^1 K_2'' k_2 [-(C_X^1 n + \Gamma_{y_1 y_1}^1)(mD_1'' + K_1'') + P'_1(m(C_X^1 n + \Gamma_{y_1 y_1}^1) \\
&\quad + (CC_1(C_X^1 n + \Gamma_{y_1 y_1}^1) + nq_1^2)(mD_1'' + K_1''))][-P'_2(C_{qq}^2 q_2(C_X^2 + C_{X X}^2 n y_2) \\
&\quad + C_{qX}^2 y_2(C_X^2 n + \Gamma_{y_2 y_2}^2)) + (P'_2)^2(C_{qq}^2 q_2(q_2^2 + 2CC_2(C_X^2 + C_{X X}^2 n y_2)) \\
&\quad + 2y_2(C_{qX}^2 CC_2 + q_2)(C_X^2 n + \Gamma_{y_2 y_2}^2)) - (P'_2)^3 CC_2(C_{qq}^2 q_2(q_2^2 + CC_2 C_X^2 + C_{X X}^2 CC_2 n y_2) \\
&\quad + y_2(C_{qX}^2 CC_2 + 2q_2)(C_X^2 n + \Gamma_{y_2 y_2}^2)) + C_{qq}^2 q_2^2 y_2 P'_2(C_X^2 n + \Gamma_{y_2 y_2}^2)] > 0
\end{aligned}$$

A.5 Proof of Lemma 1

To obtain the comparative-static effects with respect to the feed-in tariffs, we differentiate equations (1.2), (1.3), and (1.29)–(1.33) with respect to ζ_1 and simplify via the envelope theorem. This yields the following system of equations:

Aggregate electricity production:

$$\frac{\partial Q_1}{\partial \zeta_1} = \int_0^{X_1} \frac{\partial q_1(\tilde{x})}{\partial \zeta_1} d\tilde{x} + q_1(X_1) \frac{\partial X_1}{\partial \zeta_1} + m \frac{\partial k_1}{\partial \zeta_1} \quad (\text{A.45})$$

$$\frac{\partial Q_2}{\partial \zeta_1} = \int_0^{X_2} \frac{\partial q_2(\tilde{x})}{\partial \zeta_1} d\tilde{x} + q_2(X_2) \frac{\partial X_2}{\partial \zeta_1} + m \frac{\partial k_2}{\partial \zeta_1} \quad (\text{A.46})$$

Production of electricity by intra-marginal RES-E operators:

$$\frac{\partial q_1(\tilde{x})}{\partial \zeta_1} = \frac{1}{C_{qq}^1(q_1(\tilde{x}), \tilde{x})} \quad \forall \tilde{x} \leq X_1 \quad (\text{A.47})$$

$$\frac{\partial q_2(\tilde{x})}{\partial \zeta_1} = 0 \quad \forall \tilde{x} \leq X_2 \quad (\text{A.48})$$

Production of electricity by fossil-fuel utilities:

$$0 = [P'_1(Q_1) + P''_1(Q_1)k_1] \frac{\partial Q_1}{\partial \zeta_1} + [P'_1(Q_1) - K''_1(k_1)] \frac{\partial k_1}{\partial \zeta_1} \quad (\text{A.49})$$

$$0 = [P'_2(Q_2) + P''_2(Q_2)k_2] \frac{\partial Q_2}{\partial \zeta_1} + [P'_2(Q_2) - K''_2(k_2)] \frac{\partial k_2}{\partial \zeta_1} \quad (\text{A.50})$$

Output of RES-E equipment firms:

$$0 = \frac{\partial b_1}{\partial \zeta_1} - [\Gamma^1_{y_1 y_1}(y_1) + \delta \Gamma^2_{LL}(y_2, L)(1 + (n - 1)\varepsilon)] \frac{\partial y_1}{\partial \zeta_1} \quad (\text{A.51})$$

$$- \delta \Gamma^2_{y_2 L}(y_2, L) \frac{\partial y_2}{\partial \zeta_1} \quad (\text{A.52})$$

$$0 = \frac{\partial b_2}{\partial \zeta_1} - \Gamma^2_{y_2 L}(y_2, L)(1 + (n - 1)\varepsilon) \frac{\partial y_1}{\partial \zeta_1} - \Gamma^2_{y_2 y_2}(y_2, L) \frac{\partial y_2}{\partial \zeta_1} \quad (\text{A.53})$$

Total number of RES-E equipment:

$$\frac{\partial X_1}{\partial \zeta_1} = n \frac{\partial y_1}{\partial \zeta_1} \quad (\text{A.54})$$

$$\frac{\partial X_2}{\partial \zeta_1} = n \frac{\partial y_2}{\partial \zeta_1} \quad (\text{A.55})$$

RES-E equipment prices:

$$\frac{\partial b_1}{\partial \zeta_1} = q_1(X_1) - C^1_X(q_1(X_1), X_1) \frac{\partial X_1}{\partial \zeta_1} \quad (\text{A.56})$$

$$\frac{\partial b_2}{\partial \zeta_1} = -C^2_X(q_2(X_2), X_2) \frac{\partial X_2}{\partial \zeta_1} \quad (\text{A.57})$$

Electricity prices:

$$\frac{\partial p_1}{\partial \zeta_1} = P'(Q_1) \frac{\partial Q_1}{\partial \zeta_1} \quad (\text{A.58})$$

$$\frac{\partial p_2}{\partial \zeta_1} = P'(Q_2) \frac{\partial Q_2}{\partial \zeta_1} \quad (\text{A.59})$$

$$\begin{aligned}
\frac{\partial Q_1}{\partial \zeta_1} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 (K_1'' - P_1') (K_2'' - P_2' - m(P_2' + P_2'' k_2)) [(C_X^1 n + \Gamma_{y_1 y_1}^1) (C_X^2 n + \Gamma_{y_2 y_2}^2) \\
&\quad + (1 + (n-1)\varepsilon) (C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2}^{\text{Condition 1}} - (\Gamma_{Ly_2}^2)^2)] > 0 \\
\frac{\partial Q_2}{\partial \zeta_1} &= -\frac{1}{Det} C_{qq}^1 C_{qq}^2 (1 + (n-1)\varepsilon) n (K_2'' - P_2') (K_1'' - P_1' - m(P_1' + P_1'' k_1)) q_1 q_2 \Gamma_{y_2 L}^2 > 0 \\
\frac{\partial b_1}{\partial \zeta_1} &= -\frac{1}{Det} C_{qq}^1 C_{qq}^2 (K_1'' - P_1' - m(P_1' + P_1'' k_1)) (-K_2'' + P_2' + m(P_2' + P_2'' k_2)) q_1 \\
&\quad [\Gamma_{y_1 y_1}^1 (C_X^2 n + \Gamma_{y_2 y_2}^2) + (1 + (n-1)\varepsilon) \delta (C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2}^{\text{Condition 1}} - (\Gamma_{Ly_2}^2)^2)] > 0 \\
\frac{\partial b_2}{\partial \zeta_1} &= -\frac{1}{Det} C_{qq}^1 C_{qq}^2 C_X^2 n (1 + (n-1)\varepsilon) (K_1'' - P_1' - m(P_1' + P_1'' k_1)) \\
&\quad (P_2' - K_2'' + m(P_2' + P_2'' k_2)) q_1 \Gamma_{y_2 L}^2 < 0
\end{aligned}$$

For the comparative-static with respect to ζ_2 , equations (A.47), (A.48), (A.56), (A.57), (A.60) and (A.61) change as follows:

$$\frac{\partial q_1(\tilde{x})}{\partial \zeta_2} = 0 \tag{A.62}$$

$$\frac{\partial q_2(\tilde{x})}{\partial \zeta_2} = \frac{1}{C_{qq}^2(q_2(\tilde{x}), \tilde{x})} \tag{A.63}$$

$$\frac{\partial b_1}{\partial \zeta_2} = -C_X^1(q_1(X_1), X_1) \frac{\partial X_1}{\partial \zeta_2} \tag{A.64}$$

$$\frac{\partial b_2}{\partial \zeta_2} = q_2(X_2) - C_X^2(q_2(X_2), X_2) \frac{\partial X_2}{\partial \zeta_2} \tag{A.65}$$

$$\frac{\partial Q_1}{\partial \zeta_1} = q_1(X_1) \frac{\partial X_1}{\partial \zeta_1} + m \frac{\partial k_1}{\partial \zeta_1} \tag{A.66}$$

$$\frac{\partial Q_2}{\partial \zeta_1} = C C_2 + q_2(X_2) \frac{\partial X_2}{\partial \zeta_1} + m \frac{\partial k_2}{\partial \zeta_1} \tag{A.67}$$

A.5 Proof of Lemma 1

where $CC_2 = \int_0^{X_2} \frac{1}{C_{qq}^2(q_2(\tilde{x}), \tilde{x})} d\tilde{x}$. The solution of the system of equations yields the following results for the comparative-static effects with respect to ζ_2 :

$$\begin{aligned}
\frac{\partial q_1}{\partial \zeta_2} &= 0 \\
\frac{\partial q_2}{\partial \zeta_2} &= -\frac{1}{Det} C_{qq}^1 (K_1'' - P_1' - m(P_1' + P_1'' k_1)) (-K_2'' + P_2' + m(P_2' + P_2'' k_2)) \\
&\quad [(C_X^1 n + \Gamma_{y_1 y_1}^1) (C_X^2 n + \Gamma_{y_2 y_2}^2) + (1 + (n-1)\varepsilon) \delta (C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2}^{\text{Condition 1}} - (\Gamma_{Ly_2}^2)^2)] > 0 \\
\frac{\partial k_1}{\partial \zeta_2} &= -\frac{1}{Det} C_{qq}^1 C_{qq}^2 n (K_2'' - P_2' - m(P_2' + P_2'' k_2)) (P_1' + P_1'' k_1) q_1 q_2 \delta \Gamma_{y_2 L}^2 < 0 \\
\frac{\partial k_2}{\partial \zeta_2} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 (P_2' + P_2'' k_2) (K_1'' - P_1' - m(P_1' + P_1'' k_1)) \\
&\quad [(C_X^1 n + \Gamma_{y_1 y_1}^1) ((C_X^2 n + \Gamma_{y_2 y_2}^2) CC_2 + n q_2^2) \\
&\quad + (1 + (n-1)\varepsilon) \delta (\Gamma_{LL}^2 n q_2^2 + CC_2 (C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2}^{\text{Condition 1}} - (\Gamma_{Ly_2}^2)^2))] < 0 \\
\frac{\partial y_1}{\partial \zeta_2} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 (K_1'' - P_1' - m(P_1' + P_1'' k_1)) (-K_2'' + P_2' + m(P_2' + P_2'' k_2)) q_2 \delta \Gamma_{y_2 L}^2 > 0 \\
\frac{\partial y_2}{\partial \zeta_2} &= -\frac{1}{Det} C_{qq}^1 C_{qq}^2 (K_1'' - P_1' - m(P_1' + P_1'' k_1)) (-K_2'' + P_2' + m(P_2' + P_2'' k_2)) q_2 \\
&\quad (C_X^1 n + \Gamma_{y_1 y_1}^1 + (1 + (n-1)\varepsilon) \delta \Gamma_{LL}^2) > 0 \\
\frac{\partial Q_1}{\partial \zeta_2} &= -\frac{1}{Det} C_{qq}^1 C_{qq}^2 n (K_1'' - P_1') (K_2'' - P_2' - m(P_2' + P_2'' k_2)) q_1 q_2 \delta \Gamma_{y_2 L}^2 > 0 \\
\frac{\partial Q_2}{\partial \zeta_2} &= \frac{1}{Det} C_{qq}^1 C_{qq}^2 (K_2'' - P_2') (K_1'' - P_1' - m(P_1' + P_1'' k_1)) \\
&\quad [(C_X^1 n + \Gamma_{y_1 y_1}^1) ((C_X^2 n + \Gamma_{y_2 y_2}^2) CC_2 + n q_2^2) \\
&\quad + (1 + (n-1)\varepsilon) \delta (\Gamma_{LL}^2 n q_2^2 + CC_2 (C_X^2 n \Gamma_{LL}^2 + \overbrace{\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2}^{\text{Condition 1}} - (\Gamma_{Ly_2}^2)^2))] > 0 \\
\frac{\partial b_1}{\partial \zeta_2} &= -\frac{1}{Det} C_{qq}^1 C_{qq}^2 C_X^1 n (K_1'' - P_1' - m(P_1' + P_1'' k_1)) (P_2' - K_2'' + m(P_2' + P_2'' k_2)) q_1 \delta \Gamma_{y_2 L}^2 < 0 \\
\frac{\partial b_2}{\partial \zeta_2} &= -\frac{1}{Det} C_{qq}^1 C_{qq}^2 (K_1'' - P_1' - m(P_1' + P_1'' k_1)) (-K_2'' + P_2' + m(P_2' + P_2'' k_2)) q_2 \\
&\quad [\Gamma_{y_2 y_2}^2 (C_X^1 n + \Gamma_{y_1 y_1}^1) + (1 + (n-1)\varepsilon) \delta (\Gamma_{LL}^2 \Gamma_{y_2 y_2}^2 - (\Gamma_{Ly_2}^2)^2)] > 0
\end{aligned}$$

The derivation of the comparative-static effects of increasing the feed-in tariffs

on the endogenous variables when there is oligopolistic competition in the RES-E equipment industry follows the same steps as described at the beginning of this section, except that we now use the first-order conditions for RES-E equipment producers given by equations (1.34) and (1.35). From the free-entry condition we define

$$\tilde{B}(X_t, \zeta_t) = \zeta_t q_t(X_t) - C_t(q_t(X_t), X_t). \quad (\text{A.68})$$

Differentiating equation (A.68) with respect to X_t yields

$$\tilde{B}_X(X_t, \zeta_t) = [\zeta_t q_t(X_t) - C_{q_t}^t(q_t(X_t), X_t)]q_t'(X_t) - C_{X_t}^t(q_t(X_t), X_t). \quad (\text{A.69})$$

In equation (A.69) the expression $\zeta_t q_t(X_t) - C_{q_t}^t(q_t(X_t), X_t) = 0$ (following from the first-order conditions of the renewable electricity producers). Inserting (A.68) and (A.69) into the first-order conditions of the RES-E equipment producers (1.22) and (1.23) then gives the following expressions:

$$\begin{aligned} 0 &= \zeta_1 q_1(X_1) - C^1(q_1, X_1) - C_X^1(q_1, X_1)y_1 - \Gamma_{y_1}^1 \\ &\quad - \delta[C_X^2(q_2, X_2)(n-1)\frac{\partial \tilde{y}_2}{\partial y_1} + \Gamma_L^2(y_2, L)] \end{aligned} \quad (\text{A.70})$$

$$0 = \zeta_2 q_2(X_2) - C^2(q_2, X_2) - C_X^2(q_2, X_2)y_2 - \Gamma_{y_2}^2 \quad (\text{A.71})$$

Differentiating (A.70) and (A.71) with respect to the feed-in tariff in the first and second period ζ_1 and ζ_2 yields:

$$\begin{aligned} -q_1(X_1) &= -C_{q_X}^1(q_1, X_1)y_1 \frac{\partial q_1(X_1)}{\partial \zeta_1} \\ &\quad - [C_X^1(q_1, X_1) + C_{X_X}^1(q_1, X_1)y_1] \frac{\partial X_1}{\partial \zeta_1} \\ &\quad - [C_X^1(q_1, X_1) + \Gamma_{y_1 y_1}^1(y_1) + \delta \Gamma_{LL}^2(1 + (n-1)\varepsilon)] \frac{\partial y_1}{\partial \zeta_1} \\ &\quad - \delta C_{q_X}^2(q_2, X_2)(n-1) \frac{\partial \tilde{y}_2}{\partial y_1} \frac{\partial q_2(X_2)}{\partial \zeta_1} \\ &\quad - \delta C_{X_X}^2(q_2, X_2)(n-1) \frac{\partial \tilde{y}_2}{\partial y_1} \frac{\partial X_2}{\partial \zeta_1} - \delta \Gamma_{y_2 L}^2(y_2, L) \frac{\partial y_2}{\partial \zeta_1} \end{aligned} \quad (\text{A.72})$$

$$0 = -C_{qX}^2(q_2, X_2)y_2 \frac{\partial q_2(X_2)}{\partial \zeta_1} \quad (\text{A.73})$$

$$\begin{aligned} & -[C_X^2(q_2, X_2) + C_{XX}^2(q_2, X_2)y_2] \frac{\partial X_2}{\partial \zeta_1} \\ & -\Gamma_{y_2y_2}^2(y_2, L) \frac{\partial y_2}{\partial \zeta_1} - \Gamma_{y_2L}^2(y_2, L)(1 + (n-1)\varepsilon) \frac{\partial y_1}{\partial \zeta_1} \end{aligned}$$

$$0 = -C_{qX}^1(q_1, X_1)y_1 \frac{\partial q_1(X_1)}{\partial \zeta_2} \quad (\text{A.74})$$

$$\begin{aligned} & -[C_X^1(q_1, X_1) + C_{XX}^1(q_1, X_1)y_1] \frac{\partial X_1}{\partial \zeta_2} \\ & -[C_X^1(q_1, X_1) + \Gamma_{y_1y_1}^1(y_1) + \delta\Gamma_{LL}^2(1 + (n-1)\varepsilon)] \frac{\partial y_1}{\partial \zeta_2} \end{aligned}$$

$$\begin{aligned} & -\delta C_{qX}^2(q_2, X_2)(n-1) \frac{\partial \tilde{y}_2}{\partial y_1} \frac{\partial q_2(X_2)}{\partial \zeta_2} \\ & -\delta C_{XX}^2(q_2, X_2)(n-1) \frac{\partial \tilde{y}_2}{\partial y_1} \frac{\partial X_2}{\partial \zeta_2} - \delta\Gamma_{y_2L}^2(y_2, L) \frac{\partial y_2}{\partial \zeta_2} \end{aligned}$$

$$-q_2(X_2) = -C_{qX}^2(q_2, X_2)y_2 \frac{\partial q_2(X_2)}{\partial \zeta_2} \quad (\text{A.75})$$

$$\begin{aligned} & -[C_X^2(q_2, X_2) + C_{XX}^2(q_2, X_2)y_2] \frac{\partial X_2}{\partial \zeta_2} \\ & -\Gamma_{y_2y_2}^2(y_2, L) \frac{\partial y_2}{\partial \zeta_2} - \Gamma_{y_2L}^2(y_2, L)(1 + (n-1)\varepsilon) \frac{\partial y_1}{\partial \zeta_2} \end{aligned}$$

We can now solve the system of equations for the comparative-static effects with respect to the feed-in tariff for the case of imperfect competition among RES-E equipment producers. The signs of the comparative-static effects are in line with the case of perfect competition (i.e. Lemma 1), but require one additional assumption to ensure unambiguity:

Condition 4 $C_{qq}^1 q_1 - C_{qx}^1 y_1 \geq 0$,

If Condition 4 holds and $\partial \tilde{y}_2 / \partial y_1 \approx 0$, the comparative-static effects with respect to ζ_1 and ζ_2 yield the following expressions, where Det denotes the determinant:

$$\begin{aligned} Det &= -C_{qq}^1 C_{qq}^2 (K_1'' - P_1' - m(P_1' + P_1'' k_1))(P_2' - K_2'' + m(P_2' + P_2'' k_2)) \\ & [(C_X^1 + n(C_X^1 + C_{XX}^1 y_1) + \Gamma_{yy}^1)(n(C_X^2 + C_{XX}^2 y_2) + \Gamma_{yy}^2) \\ & + (1 + (n-1)\varepsilon)\delta(nC_X^2 \Gamma_{LL}^2 + \Gamma_{LL}^2 \Gamma_{yy}^2 - (\Gamma_{yL}^2)^2 + nC_{XX}^2 y_2 \Gamma_{LL}^2)] > 0 \end{aligned}$$

$$\begin{aligned}
\frac{\partial X_1}{\partial \zeta_1} &= -\frac{1}{\text{Det}} C_{qq}^2 n(K_1'' - P_1' - m(P_1' + P_1'' k_1))(P_2' - K_2'' + m(P_2' + P_2'' k_2)) \\
&\quad \underbrace{(C_{qq}^1 q_1 - C_{qX}^1 y_1) \Gamma_{yL}^2 (C_X^2 + C_{XX}^2 n y_2 + \Gamma_{yy}^2)}_{\text{Condition 4}} > 0 \\
\frac{\partial X_2}{\partial \zeta_1} &= \frac{1}{\text{Det}} C_{qq}^2 (1 + (n-1)\varepsilon) n(K_1'' - P_1' - m(P_1' + P_1'' k_1)) \\
&\quad (P_2' - K_2'' + m(P_2' + P_2'' k_2)) \underbrace{(C_{qq}^1 q_1 - C_{qX}^1 y_1) \Gamma_{yL}^2}_{\text{Condition 4}} > 0 \\
\frac{\partial Q_1}{\partial \zeta_1} &= \frac{1}{\text{Det}} C_{qq}^2 (K_1'' - P_1')(K_2'' - P_2' - m(P_2' + P_2'' k_2)) [(C_X^2 + C_{XX}^2 n y_2 + \Gamma_{yy}^2) \\
&\quad \underbrace{((C_{qq}^1 q_1 - C_{qX}^1 y_1) n q_1 + C_{qq}^1 (C_X^1 C C_1 (1+n) + n C_{XX}^1 C C_1 y_1 + C C_1 \Gamma_{yy}^1))}_{\text{Condition 4}} \\
&\quad + C_{qq}^1 C C_1 (1 + (n-1)\varepsilon) \delta (C_X^2 n \Gamma_{LL}^2 + \underbrace{\Gamma_{LL}^2 \Gamma_{yy}^2 - (\Gamma_{yL}^2)^2}_{\text{Condition 1}} + C_{XX}^2 n y_2 \Gamma_{LL}^2)] > 0 \\
\frac{\partial Q_2}{\partial \zeta_1} &= -\frac{1}{\text{Det}} C_{qq}^2 (1 + (n-1)\varepsilon) n(K_1'' - P_1' - m(P_1' + P_1'' k_1)) \\
&\quad (K_2'' - P_2') \underbrace{(C_{qq}^1 q_1 - C_{qX}^1 y_1) \Gamma_{yL}^2}_{\text{Condition 4}} > 0 \\
\frac{\partial q_1}{\partial \zeta_2} &= 0 \\
\frac{\partial q_2}{\partial \zeta_2} &= -\frac{1}{\text{Det}} C_{qq}^1 (K_1'' - P_1' - m(P_1' + P_1'' k_1))(P_2' - K_2'' + m(P_2' + P_2'' k_2)) \\
&\quad [(C_X^1 + n(C_X^1 + C_{XX}^1 y_1) + \Gamma_{yy}^1) (n(C_X^2 + C_{XX}^2 y_2) + \Gamma_{yy}^2) \\
&\quad + (1 + (n-1)\varepsilon) \delta (n C_X^2 \Gamma_{LL}^2 + \underbrace{\Gamma_{LL}^2 \Gamma_{yy}^2 - (\Gamma_{yL}^2)^2}_{\text{Condition 1}} + n C_{XX}^2 \Gamma_{LL}^2 y_2)] > 0 \\
\frac{\partial y_1}{\partial \zeta_2} &= \frac{1}{\text{Det}} C_{qq}^1 (K_1'' - P_1' - m(P_1' + P_1'' k_1))(P_2' - K_2'' + m(P_2' + P_2'' k_2)) \\
&\quad \underbrace{(C_{qq}^2 q_2 - C_{qX}^2 y_2) \delta \Gamma_{yL}^2}_{\text{Condition 4}} > 0 \\
\frac{\partial y_2}{\partial \zeta_2} &= -\frac{1}{\text{Det}} C_{qq}^1 (K_1'' - P_1' - m(P_1' + P_1'' k_1))(P_2' - K_2'' + m(P_2' + P_2'' k_2)) \\
&\quad \underbrace{[(C_{qq}^2 q_2 - C_{qX}^2 y_2) (C_X^1 + n(C_X^1 + C_{XX}^1 y_1) + \Gamma_{yy}^1)]}_{\text{Condition 4}} \\
&\quad + (1 + (n-1)\varepsilon) \delta \Gamma_{LL}^2 \underbrace{(C_{qq}^2 q_2 - C_{qX}^2 y_2)}_{\text{Condition 4}} > 0 \\
\frac{\partial k_1}{\partial \zeta_2} &= -\frac{1}{\text{Det}} C_{qq}^1 n(P_1' + P_1'' k_1)(K_2'' - P_2' - m(P_2' + P_2'' k_2)) q_1 \\
&\quad \underbrace{(C_{qq}^2 q_2 - C_{qX}^2 y_2) \delta \Gamma_{yL}^2}_{\text{Condition 4}} > 0
\end{aligned}$$

$$\begin{aligned}
\frac{\partial k_2}{\partial \zeta_2} &= \frac{1}{Det} C_{qq}^1 (K_1'' - P_1' - m(P_1' + P_1'' k_1)) (P_2' + P_2'' k_2) [(C_X^1 (n+1) + C_{XX}^1 n y_1 + \Gamma_{yy}^1)] \\
&\quad \underbrace{[(C_{qq}^2 q_2 - C_{qX}^2 y_2) n q_2 + C_{qq}^2 n (C_X^2 C C_2 + C_{XX}^2 C C_2 y_2) + C_{qq}^2 C C_2 \Gamma_{yy}^2]}_{\text{Condition 4}} \\
&\quad + (1 + (n-1)\varepsilon) [n q_2 \Gamma_{LL}^2 (C_{qq}^2 q_2 - C_{qX}^2 y_2) + C_{qq}^2 (n C C_2 \Gamma_{LL}^2 (C_X^2 + C_{XX}^2 y_2)) \\
&\quad + C C_2 (\Gamma_{LL}^2 \Gamma_{yy}^2 - (\Gamma_{yL}^2)^2)] < 0 \\
\frac{\partial b_1}{\partial \zeta_2} &= -\frac{1}{Det} C_{qq}^1 C_X^1 n (K_1'' - P_1' - m(P_1' + P_1'' k_1)) (P_2' - K_2'' + m(P_2' + P_2'' k_2)) \\
&\quad \underbrace{(C_{qq}^2 q_2 - C_{qX}^2 y_2) \delta \Gamma_{yL}^2}_{\text{Condition 4}} < 0 \\
\frac{\partial b_2}{\partial \zeta_2} &= -\frac{1}{Det} C_{qq}^1 (K_1'' - P_1' - m(P_1' + P_1'' k_1)) (P_2' - K_2'' + m(P_2' + P_2'' k_2)) \\
&\quad [(C_X^1 (n+1) + C_{XX}^1 n y_1 + \Gamma_{yy}^1) (C_{qX}^2 C_X^2 n y_2 + C_{qq}^2 q_2 (C_{XX}^2 n y_2 + \Gamma_{yy}^2)) + \\
&\quad (1 + (n-1)\varepsilon) \delta [(C_{qX}^2 C_X^2 + C_{qq}^2 q_2 C_{XX}^2) n y_2 \Gamma_{LL}^2 + C_{qq}^2 q_2 (\Gamma_{LL}^2 \Gamma_{yy}^2 - (\Gamma_{yL}^2)^2)]] > 0 \\
\frac{\partial X_1}{\partial \zeta_2} &= \frac{1}{Det} C_{qq}^1 n (K_1'' - P_1' - m(P_1' + P_1'' k_1)) (P_2' - K_2'' + m(P_2' + P_2'' k_2)) \\
&\quad \underbrace{(C_{qq}^2 q_2 - C_{qX}^2 y_2) \delta \Gamma_{yL}^2}_{\text{Condition 4}} > 0 \\
\frac{\partial X_2}{\partial \zeta_2} &= -\frac{1}{Det} C_{qq}^1 n (K_1'' - P_1' - m(P_1' + P_1'' k_1)) (P_2' - K_2'' + m(P_2' + P_2'' k_2)) \underbrace{[(C_{qq}^2 q_2 - C_{qX}^2 y_2)]}_{\text{Condition 4}} \\
&\quad (C_X^1 (n+1) + C_{XX}^1 n y_1 + \Gamma_{yy}^1) + (1 + (n-1)\varepsilon) \delta \Gamma_{LL}^2 \underbrace{(C_{qq}^2 q_2 - C_{qX}^2 y_2)}_{\text{Condition 4}} > 0 \\
\frac{\partial Q_1}{\partial \zeta_2} &= -\frac{1}{Det} C_{qq}^1 n (K_1'' - P_1') (K_2'' - P_2' - m(P_2' + P_2'' k_2)) \\
&\quad \underbrace{(C_{qq}^2 q_2 - C_{qX}^2 y_2) \delta \Gamma_{yL}^2}_{\text{Condition 4}} > 0 \\
\frac{\partial Q_2}{\partial \zeta_2} &= \frac{1}{Det} C_{qq}^1 (K_1'' - P_1' - m(P_1' + P_1'' k_1)) (K_2'' - P_2') [(C_X^1 (n+1) + C_{XX}^1 n y_1 + \Gamma_{yy}^1)] \\
&\quad \underbrace{[(C_{qq}^2 q_2 - C_{qX}^2 y_2) n q_2 + C_{qq}^2 n (C_X^2 C C_2 + C_{XX}^2 C C_2 y_2) + C_{qq}^2 C C_2 \Gamma_{yy}^2]}_{\text{Condition 4}} \\
&\quad + (1 + (n-1)\varepsilon) [n q_2 \Gamma_{LL}^2 (C_{qq}^2 q_2 - C_{qX}^2 y_2) + C_{qq}^2 (n C C_2 \Gamma_{LL}^2 (C_X^2 + C_{XX}^2 y_2)) \\
&\quad + C C_2 (\Gamma_{LL}^2 \Gamma_{yy}^2 - (\Gamma_{yL}^2)^2)] > 0
\end{aligned}$$

A.6 Derivation of the second-best optimal feed-in tariffs

The second-best optimal feed-in tariffs are obtained by differentiating welfare given by (1.5) with respect to the feed-in tariff rates ζ_1 and ζ_2 , yielding the following expression:

$$\begin{aligned}
 \frac{\partial W}{\partial \zeta_1} &= [P_1(Q_1) - K'_1(k_1) - D'_1(mk_1)]m \frac{\partial k_1}{\partial \zeta_1} & (A.76) \\
 &+ [P_1(Q_1) - C_q^1(q_1(X_1), X_1) - \Gamma_{y_1}^1(y_1) - \delta(1 + (n-1)\varepsilon)\Gamma_L^2(y_2, L)] \frac{\partial X_1}{\partial \zeta_1} \\
 &+ \int_0^{X_1} [P_1(Q_1) - C_q^1(q_1(\tilde{x}), \tilde{x})] \frac{\partial q_1(\tilde{x})}{\partial \zeta_1} d\tilde{x} \\
 &+ \delta [P_2(Q_2) - K'_2(k_2) - D'_2(mk_2)]m \frac{\partial k_2}{\partial \zeta_1} \\
 &+ \delta [P_2(Q_2) - C_q^2(q_2(X_2), X_2) - \Gamma_{y_2}^2(y_2, L)] \frac{\partial X_2}{\partial \zeta_1} \\
 &+ \delta \int_0^{X_2} [P_2(Q_2) - C_q^2(q_2(\tilde{x}), \tilde{x})] \frac{\partial q_2(\tilde{x})}{\partial \zeta_1} d\tilde{x} = 0.
 \end{aligned}$$

Expanding (A.76) with $\zeta_t q_t \frac{\partial X_t}{\partial \zeta_t} - \zeta_t q_t \frac{\partial X_t}{\partial \zeta_t} + nb_t \frac{\partial y_t}{\partial \zeta_t} - nb_t \frac{\partial y_t}{\partial \zeta_t}$ for $t = 1, 2$ and using the behavioral conditions of the firms allows us to simplify (A.76) as follows:

$$\begin{aligned}
 0 &= [-P'_1(Q_1) + \tau_1 - D'_1(mk_1)]m \frac{\partial k_1}{\partial \zeta_1} & (A.77) \\
 &+ [P_1(Q_1) - \zeta_1][q_1(X_1) \frac{\partial X_1}{\partial \zeta_1} + \int_0^{X_1} \frac{\partial q_1(\tilde{x})}{\partial \zeta_1} d\tilde{x}] \\
 &- \delta \Gamma_L^2(y_2, L)(n-1)\varepsilon n \frac{\partial y_1}{\partial \zeta_1} + \delta [-P'_2(Q_2) + \tau_2 - D'_2(mk_2)]m \frac{\partial k_2}{\partial \zeta_1} \\
 &+ \delta [P_2(Q_2) - \zeta_2]q_2(X_2) \frac{\partial X_2}{\partial \zeta_1}.
 \end{aligned}$$

A.6 Derivation of the second-best optimal feed-in tariffs

Analogously, differentiating welfare with respect to ζ_2 and simplifying yields:

$$\begin{aligned}
 0 = & [-P_1'(Q_1) + \tau_1 - D_1'(mk_1)]m \frac{\partial k_1}{\partial \zeta_2} + [P_1(Q_1) - \zeta_1]q_1(X_1) \frac{\partial X_1}{\partial \zeta_2} & (A.78) \\
 & - \delta \Gamma_L^2(y_2, L)(n-1)\varepsilon n \frac{\partial y_1}{\partial \zeta_2} \\
 & + \delta [-P_2'(Q_2) + \tau_2 - D_2'(mk_2)]m \frac{\partial k_2}{\partial \zeta_2} \\
 & + \delta [P_2(Q_2) - \zeta_2] [q_2(X_2) \frac{\partial X_2}{\partial \zeta_2} + \int_0^{X_2} \frac{\partial q_2(\tilde{x})}{\partial \zeta_2} d\tilde{x}].
 \end{aligned}$$

Solving the latter two expressions for ζ_1 and ζ_2 yields the second-best optimal feed-in tariffs given in section 1.5.1.

Appendix B

Appendix B

B.1 Construction of weather indices

We construct several daily temperature and precipitation indices from weather stations in Germany, France, Spain, and Italy. For the calculation of the indices we use different methodologies that have been used in the pertinent literature on emission prices and weather variables. The temperature and precipitation data have been obtained from the publicly available European climate and assessment dataset (<http://eca.knmi.nl/>).

B.1.1 Daily mean temperature and precipitation indices

The mean temperature index is aggregated by multiplying each individual series with its respective regional population weight (following Valor *et al.*, 2001), and the daily precipitation index is aggregated by multiplying the series with weights representing hydroelectric capacity installed in each country:

$$X_t = \sum_{n=1}^N x_{l,t} w_{l,t}, \quad (\text{B.1})$$

where $X = Temp, Prec$ represents daily mean temperature and precipitation on day t , $x_{l,t}$ is the value of the respective weather variable at location l on day t , $w_{l,t}$ is the regional-population or hydroelectric-capacity weight belonging to

B.1 Construction of weather indices

each location, and N represents the number of weather stations ($N = 52$ for the temperature index and $N = 50$ for the precipitation index).

To obtain the weather indices used in model specification 1, we then calculate the deviation of the daily indices in our sample period from their daily historical means:

$$Dev_t = X_t - E_{t-1}[X_t], \quad (\text{B.2})$$

where $E_{t-1}[X_t]$ represents the daily historical mean temperature or precipitation index. The daily historical weather index is calculated as the 29-year average from 1 January 1978 to 31 December 2006:

$$E_{t-1}[X_t] = \frac{1}{29} \sum_{y=1978}^{2006} X_{dy}, \quad (\text{B.3})$$

where $d = 1, 2, \dots, 365$ is the calendar day corresponding to day t and year y .

According to Hintermann (2010), traders in the energy markets are likely to take into account not only the weather on a given day, but also past and forecasted weather. We therefore calculate 5-day moving averages of the daily weather deviations:

$$MA_{X,t} = \sum_{k=t-2}^{t+2} \frac{X_k - E_{k-1}[X_k]}{5}. \quad (\text{B.4})$$

For model specification 2, we construct indices that account for extreme weather conditions, i.e. extremely hot, cold, rainy, and dry days. For this purpose, we follow Mansanet-Bataller *et al.* (2007) and calculate the percentiles of both indices X_t in (B.1) and separate the values of temperature and precipitation lying in the 5th and the 95th percentile into four indices: $TE5_t$, $TE95_t$, $PR5_t$, and $PR95_t$. For instance, the index $TE5_t$ on any given day t will be assigned the daily mean temperature value on day t if it lies within the 5th percentile of the distribution (assuming a daily mean temperatures are normally distributed) and will be zero otherwise.

B.1.2 Degree day indices

For model specifications 3 and 4, we calculate two different indices reflecting the daily energy demand for the heating of buildings at certain locations. A degree day index is calculated on days where the average outside temperature lies below a certain threshold, determined by the base temperature below which buildings need to be heated. Different base temperatures may be used, depending on the specific heating requirements at a certain location or building.

For model specification 3, we follow Fell (2010) in calculating the daily heating-degree-day index (HDD_t):

$$HDD_{t,l} = \begin{cases} Base_{out} - Temp_{t,l} & \text{if } Temp_{t,l} < 15^\circ\text{C}, \\ 0, & \text{else.} \end{cases} \quad (\text{B.5})$$

In (B.5) HDD_t reflects the difference between the average outside temperature on day t at location l and the base outside temperature ($Base_{out}$), which is set to 15°C . Therefore, if the outside temperature on day t is greater or equal to 15°C , no heating is needed and the index is equal to zero. If the outside temperature is below 15°C , the HDD_t -index is calculated. Therefore, the lower the outside temperature, the lower is the value of the HDD_t -index.¹

For model specification 4 we calculate a German degree-day index ("Gradtagzahl" (GTZ), in German). The GTZ_t index is calculated in a similar fashion as the HDD_t index except that the base inside temperature is taken instead of the heating threshold temperature, i.e.

$$GTZ_{t,l} = \begin{cases} Base_{ins} - Temp_{t,l}, & \text{if } Temp_{t,l} < 15^\circ\text{C}, \\ 5, & \text{else.} \end{cases} \quad (\text{B.6})$$

Following the approach of the German weather service (*Deutscher Wetterdienst*), we set the inside temperature $Base_{ins}$ to 20°C . All daily average temperatures greater than 15°C are normalized to 15°C . Therefore, the value of the GTZ_t index when no heating is needed is 5. A higher value of the index thus indicates a higher heating energy demand.

¹In a similar fashion one could calculate a cooling degree day index measuring the demand for energy to cool buildings when outside temperature exceeds a certain base temperature.

We calculate the HDD_t index as a European temperature index, whereas the GTZ_t index only takes into account German temperature. The reason for calculating both indices is that some of the commodities under study are traded Europe- or even worldwide (i.e. emission allowances and coal) while the others are traded mainly in Germany (i.e. power and natural gas). In the latter case, a German temperature index may have a higher predictive power than a European index.

To account for seasonal effects, we further construct seasonal dummy variables in order to separate the impact of the temperature indices during summer months DS_t (April to October) and winter months DW_t (November to March). We also construct dummy variables for each month of the year $DMON_t$ for $MON = JAN, FEB, \dots, DEC$. Table B.1 summarizes the weather indices used in the alternative model specifications 2-4.

Table B.1: Weather indices used in the alternative model specifications

Index	Description
$TE5_t, TE95_t$	Temperature values within the 5th (95th) percentile
$PR5_t, PR95_t$	Precipitation values within the 5th (95th) percentile
HDD_t	Heating degree days
GTZ_t	Degree day number (<i>Gradtagzahl</i>)
$DMON_t$	Dummy for each month of the year ($JAN - DEC$)

B.2 Unit root tests

It is important to test for stationarity of the time series, because if the time series are integrated of an order higher than zero (i.e. they are non-stationary), the regression analysis may provide spurious correlations. A data generating process is stationary if it has time-invariant first and second moments, i.e. it is integrated of order zero, $I(0)$ for short. The Augmented Dickey-Fuller (ADF) test considers the null hypothesis that the data generating process has a unit root, i.e. it is $I(1)$, against the alternative of stationarity. Conversely, the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test considers the null hypothesis that the data

B.3 Results of the alternative model specifications

generating process is $I(0)$ against the alternative of a unit root. The value of the test statistics for both tests are reported in table B.2, where bl, pl indicates baseload and peakload prices, respectively, and the corresponding critical values are displayed at the bottom of the table. From the results of the ADF test we clearly cannot reject the null hypothesis of a unit root for all the price series at any confidence level. Moreover, according to the KPSS test we can clearly reject the null hypothesis that the price series are $I(0)$ at a 1% confidence level.

Table B.2: Unit root tests

	ADF test	KPSS test
$p_{e(bl),t}$	-0.5172	10.6457
$p_{e(pl),t}$	0.0089	10.7073
$p_{a,t}$	-0.7860	18.9861
$p_{g,t}$	0.9873	11.9530
$p_{c,t}$	-1.0018	7.1205

Selection of lags for ADF test according to Schwarz criterion. Number of lags equal to one for KPSS test. Critical values: ADF test (Davidson & MacKinnon, 1993): -3.43 (1%), -2.86 (5%), -2.57 (10%); KPSS test (Kwiatkowski *et al.*, 1992): 0.739 (1%), 0.463 (5%), 0.347 (10%).

B.3 Results of the alternative model specifications

To test the robustness of the empirical results of the VECM with orthogonal GARCH errors, we estimate the model with different specifications of the matrix of exogenous variables. In particular, we include different types of weather indices, all of which have been used in previous studies on CO_2 and energy prices.

In specification 2, the weather indices $TE5_t$, $TE95_t$, $PR5_t$, $PR95_t$ include observations lying in the 5th and 95th percentile of both temperature and precipitation series, representing extremely high and low daily mean temperatures and precipitation levels, respectively. Specification 3 includes a European heating-degree-day index (HDD_t) and the extreme precipitation indices $PR5_t$ and $PR95_t$.

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Finally, specification 4 includes only German weather indices, namely a German degree-day-index (GTZ_t) and German extreme-precipitation indices ($PR5G_t$, $PR95G_t$). In order to account for seasonal effects in the temperature series, we multiply both HDD_t and GTZ_t indices with twelve dummy variables representing each month of the calendar year. Therefore, $HDD_{i,t-1}$ for $i = 1, \dots, 12$ denotes the monthly HDD_t index obtained by multiplying the daily HDD_t index with the monthly dummy vectors, i.e. $HDD_{i,t-1} = HDD_{t-1} \times DMON_{t-1}$ for $MON = JAN, FEB, \dots, DEC$. Analogously, $GTZ_{i,t-1}$ for $i = 1, \dots, 12$ denotes the monthly GTZ_t index obtained by multiplying the daily GTZ_t index with the monthly dummy vectors, i.e. $GTZ_{i,t-1} = GTZ_{t-1} \times DMON_{t-1}$ for $MON = JAN, FEB, \dots, DEC$. The results of the alternative model specifications are presented in Tables B.3, B.4, and B.5. Overall, the estimated coefficients for the endogenous variables, the contemporaneous coefficients, and the variance coefficients do not exhibit major changes in their value or significance level throughout the different specifications, indicating that the empirical results are robust.

Concerning the significance of the alternative weather indicators, the results of baseload specification 2 (Table B.3) show that the extreme-temperature and extreme-precipitation variables have a statistically significant impact at the 5% or 10% level on at least one of the four returns of power, emission allowances, natural gas, and coal futures in the baseload specification. Similar results are obtained in peakload specification 2.

The HDD_t index used in baseload specification 3 (Table B.4) is significant at least at the 10% level for electricity returns (in February, May, and December), for EUA returns (in January and May), for natural gas returns (in April and September), and for coal returns (in May). The results of peakload specification 3 are again very similar.

Finally, in baseload specification 4 (Table B.5) the German GTZ_t index has a high explanatory power for natural gas and coal returns (in April, May, and June), and is statistically significant at the 10% level for electricity returns (in May and December), for natural gas returns (in March and September), and for coal returns (in October). In addition, the German extreme-precipitation variables used in specification 4 only have a statistically significant impact at the

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5% or 10% level on natural gas returns. Finally, the German weather indices have very little explanatory power for EUA returns, reflecting the fact that allowance prices depend on EU-wide emissions and therefore they are not influenced by weather conditions in a single country. Again, similar results are obtained in peakload specification 4.

	Independent variables	Baseload specification 2				Peakload specification 2			
		$r_{e,t}$	$r_{a,t}$	$r_{g,t}$	$r_{c,t}$	$r_{e,t}$	$r_{a,t}$	$r_{g,t}$	$r_{c,t}$
Cons.	v	34.1845 [4.42]	50.1108 [3.51]	<i>19.8459</i> [1.90]	18.1231 [1.45]	16.9391 [4.26]	29.7995 [3.43]	9.1542 [1.35]	7.0040 [0.95]
Endo.	z_{t-1}	-0.1172 [-4.41]	-0.1718 [-3.50]	<i>-0.0677</i> [-1.89]	-0.0620 [-1.45]	-0.0632 [-4.24]	-0.1112 [-3.42]	-0.0337 [-1.33]	-0.0260 [-0.94]
	$r_{e,t-1}$	0.1088 [1.50]	-0.1221 [-0.65]	0.2478 [2.50]	0.2274 [2.35]	0.1075 [1.53]	-0.1287 [-0.62]	0.1932 [2.00]	0.2081 [2.00]
	$r_{a,t-1}$	0.0296 [0.92]	0.1587 [2.13]	0.0044 [0.11]	-0.0292 [-0.63]	0.0229 [0.82]	0.1637 [2.22]	0.0263 [0.67]	-0.0124 [-0.27]
	$r_{g,t-1}$	0.0133 [0.36]	0.0355 [0.53]	-0.1106 [-1.60]	0.0849 [1.40]	0.0369 [1.17]	0.0161 [0.24]	-0.1030 [-1.51]	0.0894 [1.46]
	$r_{c,t-1}$	-0.0458 [-0.88]	-0.1217 [-1.22]	0.0086 [0.16]	-0.0828 [-1.21]	-0.0528 [-1.29]	-0.1257 [-1.37]	0.0429 [0.83]	-0.0598 [-0.94]
Exo.	OIL_{t-1}	-0.0149 [-0.53]	-0.0937 [-2.03]	0.0569 [1.36]	0.0377 [0.81]	0.0042 [0.18]	-0.0917 [-2.00]	0.0553 [1.32]	0.0372 [0.80]
	EAR_{t-1}	-0.0093 [-0.91]	-0.0523 [-2.90]	-0.0204 [-1.40]	-0.0315 [-2.59]	-0.0029 [-0.29]	-0.0492 [-2.76]	-0.0180 [-1.29]	-0.0294 [-2.50]
	$TE5_{t-1}$	-0.0438 [-0.17]	<i>1.0318</i> [1.72]	0.3142 [0.48]	0.3207 [0.35]	-0.1311 [-1.02]	0.8496 [1.37]	0.2593 [0.40]	0.2816 [0.31]
	$TE95_{t-1}$	<i>-0.0124</i> [-1.67]	-0.0142 [-0.83]	-0.0430 [-3.50]	-0.0125 [-0.92]	<i>-0.0171</i> [-1.89]	-0.0171 [-1.06]	-0.0423 [-3.41]	-0.0117 [-0.85]
	$PR5_{t-1}$	<i>-0.0386</i> [-1.75]	-0.0629 [-1.55]	-0.0758 [-2.74]	-0.0499 [-1.63]	<i>-0.0391</i> [-1.95]	-0.0656 [-1.61]	-0.0778 [-2.79]	<i>-0.0514</i> [-1.67]
	$PR95_{t-1}$	0.0023 [0.97]	0.0017 [0.36]	-0.0048 [-1.43]	0.0073 [2.04]	0.0016 [0.76]	0.0016 [0.35]	-0.0049 [-1.49]	0.0071 [1.99]
Cont.	$u_{e,t}$	0.7535 [4.51]	0.6063 [3.95]	0.5207 [4.37]	0.7318 [4.15]	0.1317 [1.44]	0.0851 [0.34]	-0.1932 [-1.50]	-1.0953 [-6.05]
	$u_{a,t}$	0.2057 [3.68]	2.2108 [7.01]	0.1930 [2.01]	0.1114 [0.63]	0.1814 [3.22]	2.2724 [6.15]	0.2439 [2.36]	0.1448 [0.88]
	$u_{g,t}$	0.0515 [1.44]	0.1659 [1.46]	1.3747 [22.63]	0.0845 [1.09]	0.0282 [0.87]	0.1322 [1.25]	1.3838 [22.24]	0.0971 [1.12]
	$u_{c,t}$	-0.0079 [-0.11]	-0.0618 [-0.27]	0.2128 [2.16]	1.0423 [5.33]	0.6259 [4.07]	0.5285 [3.61]	0.5080 [4.01]	0.7538 [3.87]
Vol.	$\omega_{\bullet,t-1}$	0.8856 [8.93]	0.8449 [5.61]	0.3402 [0.39]	0.9443 [4.95]	0.9288 [6.67]	0.8614 [5.34]	0.3123 [0.44]	0.8953 [7.36]
	$u_{\bullet,t-1}^2$	0.1060 [4.77]	0.1189 [2.06]	0.1454 [2.39]	0.0484 [1.99]	0.0572 [2.47]	0.1114 [2.14]	0.1581 [2.26]	0.0960 [4.00]

Table B.3: VECM with orthogonal GARCH errors, specification 2: mean/variance equations and contemporaneous coefficients. See table 2.6 for further details.

B.3 Results of the alternative model specifications

	Independent variables	Baseload specification 3				Peakload specification 3			
		$r_{e,t}$	$r_{a,t}$	$r_{g,t}$	$r_{c,t}$	$r_{e,t}$	$r_{a,t}$	$r_{g,t}$	$r_{c,t}$
Cons.	v	39.0828 [5.10]	48.0959 [3.26]	<i>18.9393</i> [1.74]	<i>22.3008</i> [1.74]	17.6075 [4.35]	25.2618 [2.88]	7.1903 [1.03]	8.4430 [1.14]
Endo.	z_{t-1}	-0.1341 [-5.09]	-0.1651 [-3.26]	<i>-0.0651</i> [-1.74]	<i>-0.0766</i> [-1.74]	-0.0658 [-4.35]	-0.0946 [-2.88]	-0.0270 [-1.04]	-0.0316 [-1.15]
	$r_{e,t-1}$	0.0923 [1.27]	-0.1590 [-0.85]	0.2406 [2.42]	0.2382 [2.36]	0.0641 [0.91]	-0.1858 [-0.93]	<i>0.1802</i> [1.85]	<i>0.2067</i> [1.90]
	$r_{a,t-1}$	0.0240 [0.79]	0.1470 [1.99]	0.0058 [0.15]	-0.0293 [-0.62]	0.0233 [0.89]	0.1569 [2.17]	0.0291 [0.76]	-0.0090 [-0.19]
	$r_{g,t-1}$	0.0060 [0.16]	0.0211 [0.33]	<i>-0.1203</i> [-1.72]	0.0726 [1.19]	0.0344 [1.10]	0.0076 [0.11]	-0.1103 [-1.60]	0.0785 [1.27]
	$r_{c,t-1}$	-0.0416 [-0.80]	-0.1020 [-1.02]	0.0035 [0.06]	-0.0960 [-1.38]	-0.0417 [-1.01]	-0.1039 [-1.15]	0.0391 [0.74]	-0.0680 [-1.02]
Exo.	OIL_{t-1}	-0.0220 [-0.82]	-0.1071 [-2.37]	0.0504 [1.24]	0.0332 [0.73]	-0.0002 [-0.01]	-0.1013 [-2.25]	0.0500 [1.22]	0.0335 [0.73]
	EAR_{t-1}	-0.0104 [-1.07]	-0.0565 [-3.02]	-0.0218 [-1.56]	-0.0321 [-2.57]	-0.0049 [-0.49]	-0.0545 [-2.93]	-0.0197 [-1.46]	-0.0299 [-2.44]
	$HDD_{1,t-1}$	-0.0173 [-0.78]	-0.1021 [-2.54]	0.0137 [0.44]	0.0212 [0.55]	-0.0133 [-0.78]	-0.0906 [-2.23]	0.0146 [0.47]	0.0231 [0.60]
	$HDD_{2,t-1}$	-0.0590 [-2.15]	-0.0184 [-0.22]	0.0031 [0.09]	-0.0101 [-0.24]	-0.0574 [-2.30]	-0.0093 [-0.11]	0.0100 [0.29]	-0.0002 [-0.00]
	$HDD_{3,t-1}$	0.0239 [0.64]	0.0930 [1.38]	0.0362 [0.85]	-0.0035 [-0.06]	0.0419 [1.39]	0.1090 [1.59]	0.0419 [1.01]	0.0027 [0.05]
	$HDD_{4,t-1}$	0.0649 [1.14]	0.1254 [1.38]	0.1803 [2.39]	0.0638 [1.12]	0.0495 [1.01]	0.1218 [1.33]	0.1876 [2.42]	0.0724 [1.21]
	$HDD_{5,t-1}$	0.5647 [3.73]	0.8653 [2.46]	0.6131 [1.58]	0.4100 [2.04]	0.4661 [3.05]	0.8427 [2.45]	0.5790 [1.45]	<i>0.3707</i> [1.77]
	$HDD_{6,t-1}$	0.0418 [0.14]	0.1420 [0.29]	0.3257 [1.09]	0.3044 [0.61]	0.0513 [0.25]	0.2143 [0.45]	0.3731 [1.31]	0.3616 [0.74]
	$HDD_{7,t-1}$	-0.3241 [-0.97]	0.1072 [0.07]	-0.4436 [-0.54]	-0.1869 [-0.25]	0.0165 [0.06]	0.3419 [0.22]	-0.5119 [-0.63]	-0.2152 [-0.28]
	$HDD_{8,t-1}$	0.2475 [0.46]	0.0364 [0.02]	0.6284 [0.49]	0.4943 [0.90]	0.3765 [0.67]	0.2559 [0.11]	0.6657 [0.50]	0.5574 [0.96]
	$HDD_{9,t-1}$	0.1244 [1.02]	0.2315 [1.22]	<i>0.2448</i> [1.85]	0.1052 [0.43]	0.1092 [1.14]	0.2732 [1.43]	<i>0.2556</i> [1.89]	0.1185 [0.48]
	$HDD_{10,t-1}$	0.0293 [0.82]	0.0172 [0.23]	0.0392 [0.54]	0.0449 [0.86]	0.0210 [0.66]	0.0126 [0.17]	0.0348 [0.48]	0.0408 [0.79]
	$HDD_{11,t-1}$	-0.0268 [-0.66]	-0.0295 [-0.57]	-0.0402 [-1.32]	-0.0602 [-1.49]	-0.0319 [-0.93]	-0.0356 [-0.67]	-0.0381 [-1.23]	-0.0580 [-1.38]
	$HDD_{12,t-1}$	<i>0.0446</i> [1.91]	0.0406 [1.01]	0.0273 [0.76]	0.0385 [0.95]	<i>0.0311</i> [1.67]	0.0227 [0.61]	0.0158 [0.45]	0.0254 [0.65]
	$PR5_{t-1}$	<i>-0.0400</i> [-1.88]	<i>-0.0678</i> [-1.69]	-0.0701 [-2.53]	-0.0494 [-1.61]	-0.0402 [-2.05]	<i>-0.0689</i> [-1.70]	-0.0711 [-2.54]	-0.0503 [-1.61]
	$PR95_{t-1}$	0.0021 [0.88]	0.0017 [0.37]	-0.0047 [-1.40]	0.0072 [2.08]	0.0014 [0.69]	0.0016 [0.35]	-0.0049 [-1.46]	0.0070 [2.02]
	Cont.	$u_{e,t}$	0.8239 [5.02]	0.5942 [4.01]	0.5750 [4.72]	0.9613 [4.62]	0.3390 [3.42]	0.4667 [1.96]	0.0573 [0.42]
$u_{a,t}$		0.2402 [3.54]	2.2512 [6.28]	0.2520 [2.44]	0.2452 [1.39]	<i>0.1389</i> [1.93]	2.2293 [5.62]	0.2802 [2.70]	0.2902 [2.09]
$u_{g,t}$		0.0811 [2.08]	0.1663 [1.50]	1.3945 [22.94]	<i>0.1345</i> [1.69]	0.0288 [0.74]	0.0816 [0.72]	1.3907 [22.38]	0.1561 [2.00]
$u_{c,t}$		-0.1499 [-1.97]	-0.2631 [-1.07]	0.0953 [0.89]	0.9101 [5.63]	0.6208 [4.66]	0.5194 [3.72]	0.5491 [4.45]	1.0013 [4.26]
Vol.	$\omega_{\bullet,t-1}$	0.8815 [9.20]	0.8584 [5.41]	0.2567 [0.74]	0.9462 [5.74]	0.9345 [7.15]	0.8804 [5.52]	0.1933 [0.93]	0.8975 [7.84]
	$u_{\bullet,t-1}^2$	0.1082 [4.71]	0.1120 [2.06]	0.1605 [2.61]	0.0456 [2.11]	0.0529 [2.44]	0.0989 [2.27]	0.1871 [2.61]	0.0928 [4.03]

Table B.4: VECM with orthogonal GARCH errors, specification 3: mean/variance equations and contemporaneous coefficients. See table 2.6 for further details.

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	Independent variables	Baseload specification 4				Peakload specification 4			
		$r_{e,t}$	$r_{a,t}$	$r_{g,t}$	$r_{c,t}$	$r_{e,t}$	$r_{a,t}$	$r_{g,t}$	$r_{c,t}$
Cons.	v	36.5408 [4.64]	45.8462 [2.97]	15.6035 [1.43]	15.2395 [1.19]	15.5132 [3.85]	22.9033 [2.52]	4.3895 [0.64]	2.9369 [0.40]
Endo.	z_{t-1}	-0.1263 [-4.67]	-0.1591 [-3.02]	-0.0565 [-1.51]	-0.0545 [-1.23]	-0.0591 [-3.92]	-0.0879 [-2.60]	-0.0196 [-0.76]	-0.0135 [-0.49]
	$r_{e,t-1}$	0.0955 [1.31]	-0.1567 [-0.83]	0.2594 [2.61]	0.2393 [2.40]	0.0593 [0.84]	-0.1864 [-0.93]	<i>0.1797</i> [1.86]	<i>0.1988</i> [1.83]
	$r_{a,t-1}$	0.0232 [0.75]	<i>0.1436</i> [1.95]	0.0062 [0.15]	-0.0265 [-0.56]	0.0249 [0.93]	0.1554 [2.14]	0.0321 [0.82]	-0.0058 [-0.12]
	$r_{g,t-1}$	0.0109 [0.29]	0.0335 [0.51]	<i>-0.1194</i> [-1.74]	0.0717 [1.17]	0.0407 [1.31]	0.0214 [0.33]	-0.1049 [-1.54]	0.0821 [1.33]
	$r_{c,t-1}$	-0.0425 [-0.80]	-0.1038 [-1.03]	-0.0107 [-0.19]	-0.0958 [-1.36]	-0.0422 [-1.01]	-0.1060 [-1.17]	0.0306 [0.59]	-0.0668 [-1.02]
Exo.	OIL_{t-1}	-0.0274 [-1.02]	-0.1177 [-2.62]	0.0437 [1.09]	0.0251 [0.56]	-0.0054 [-0.23]	-0.1116 [-2.49]	0.0431 [1.07]	0.0255 [0.57]
	EAR_{t-1}	-0.0107 [-1.10]	-0.0564 [-2.87]	<i>-0.0222</i> [-1.69]	-0.0315 [-2.61]	-0.0058 [-0.58]	-0.0549 [-2.85]	-0.0202 [-1.58]	-0.0296 [-2.49]
	$GTZ_{1,t-1}$	0.0018 [0.11]	-0.0353 [-1.16]	0.0383 [1.57]	0.0421 [1.43]	0.0032 [0.23]	-0.0259 [-0.86]	0.0382 [1.58]	0.0425 [1.43]
	$GTZ_{2,t-1}$	-0.0181 [-0.96]	0.0055 [0.10]	0.0331 [1.28]	0.0284 [0.95]	-0.0180 [-1.05]	0.0141 [0.27]	0.0366 [1.39]	0.0341 [1.10]
	$GTZ_{3,t-1}$	0.0231 [1.01]	0.0591 [1.41]	<i>0.0503</i> [1.71]	0.0336 [0.96]	0.0306 [1.60]	<i>0.0712</i> [1.69]	<i>0.0536</i> [1.85]	0.0377 [1.09]
	$GTZ_{4,t-1}$	0.0404 [1.51]	0.0813 [1.62]	0.1036 [2.60]	0.0857 [2.14]	0.0344 [1.49]	<i>0.0867</i> [1.73]	0.1070 [2.62]	0.0911 [2.20]
	$GTZ_{5,t-1}$	<i>0.0846</i> [1.85]	0.1182 [1.26]	0.1949 [2.77]	0.1542 [2.31]	<i>0.0773</i> [1.86]	0.1226 [1.31]	0.1901 [2.64]	0.1524 [2.22]
	$GTZ_{6,t-1}$	0.0570 [1.12]	0.0647 [0.65]	0.1397 [2.03]	0.1685 [2.08]	0.0615 [1.40]	0.0926 [0.94]	0.1500 [2.16]	0.1821 [2.22]
	$GTZ_{7,t-1}$	0.0111 [0.21]	0.0065 [0.06]	0.0953 [1.30]	0.0898 [1.03]	0.0086 [0.19]	0.0232 [0.22]	0.0949 [1.27]	0.0924 [1.03]
	$GTZ_{8,t-1}$	0.0522 [1.07]	0.1223 [1.27]	0.0768 [1.06]	0.1036 [1.33]	0.0435 [1.00]	0.1331 [1.39]	0.0808 [1.09]	0.1099 [1.37]
	$GTZ_{9,t-1}$	0.0268 [0.68]	0.0503 [0.71]	<i>0.1005</i> [1.95]	0.0682 [0.98]	0.0301 [0.89]	0.0703 [0.99]	<i>0.1023</i> [1.95]	0.0712 [1.00]
	$GTZ_{10,t-1}$	0.0261 [1.14]	0.0333 [0.72]	0.0519 [1.41]	<i>0.0590</i> [1.71]	0.0211 [1.05]	0.0371 [0.80]	0.0505 [1.36]	<i>0.0585</i> [1.69]
	$GTZ_{11,t-1}$	-0.0037 [-0.16]	0.0051 [0.14]	0.0140 [0.56]	0.0089 [0.30]	-0.0079 [-0.40]	0.0073 [0.19]	0.0157 [0.61]	0.0118 [0.38]
	$GTZ_{12,t-1}$	<i>0.0330</i> [1.79]	0.0364 [1.11]	0.0418 [1.45]	0.0461 [1.41]	<i>0.0258</i> [1.71]	0.0305 [0.95]	0.0360 [1.25]	0.0405 [1.25]
	$PR5G_{t-1}$	0.3058 [1.42]	0.5803 [1.54]	<i>0.5750</i> [1.81]	0.2293 [0.77]	0.3919 [1.97]	0.6245 [1.63]	<i>0.5610</i> [1.77]	0.2160 [0.72]
$PR95G_{t-1}$	0.0149 [0.99]	0.0218 [0.69]	0.0414 [2.06]	0.0335 [1.55]	0.0182 [1.48]	0.0249 [0.80]	<i>0.0383</i> [1.92]	0.0304 [1.42]	
Cont.	$u_{e,t}$	0.8171 [4.87]	0.6459 [4.05]	0.5811 [4.66]	0.9035 [4.60]	0.3157 [4.23]	0.4150 [2.11]	0.0852 [0.73]	-0.7982 [-5.63]
	$u_{a,t}$	0.2126 [3.75]	2.2145 [6.76]	0.2230 [2.26]	0.1736 [1.10]	0.1479 [2.36]	2.2320 [5.79]	0.2570 [2.53]	0.2760 [2.17]
	$u_{g,t}$	0.0516 [1.42]	0.1447 [1.25]	1.3805 [23.98]	0.1240 [1.52]	0.0075 [0.20]	0.0969 [0.86]	1.3868 [23.52]	0.1665 [2.15]
	$u_{c,t}$	-0.0935 [-1.60]	-0.1625 [-0.81]	0.0947 [0.99]	0.9388 [5.16]	0.5971 [4.29]	0.5076 [3.59]	0.5334 [4.16]	0.9495 [4.17]
Vol.	$\omega_{\bullet,t-1}$	0.8734 [9.92]	0.8491 [5.75]	0.1578 [0.94]	0.9499 [5.05]	0.9352 [7.17]	0.8754 [5.44]	0.1049 [0.99]	0.8976 [7.60]
	$\omega_{\bullet,t-1}^2$	0.1169 [5.08]	0.1175 [2.15]	0.1529 [3.07]	<i>0.0426</i> [1.89]	0.0524 [2.48]	0.1025 [2.26]	0.1791 [2.99]	0.0942 [4.04]

Table B.5: VECM with orthogonal GARCH errors, specification 4: mean/variance equations and contemporaneous coefficients. See table 2.6 for further details.

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Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt, dass ich meine Doktorarbeit "Analysis of Carbon Mitigation Policies: Feed-in Tariffs, Energy and Carbon Price Interactions, and Competitive Distortions on Carbon Markets" selbständig und ohne fremde Hilfe angefertigt habe und dass ich alle von anderen Autoren wörtlich übernommenen Stellen, wie auch die sich an die Gedanken anderer Autoren eng anlehnenden Ausführungen meiner Arbeit, besonders gekennzeichnet und die Quellen nach den mir angegebenen Richtlinien zitiert habe.

Kiel, den 1. Juni 2011

Johanna Reichenbach

Personal data

Birth date and place: February 8, 1981, Lörrach

Current position

2007/01 – present

Research and teaching associate

Department of Economics, Christian-Albrechts-University Kiel

- Theoretical research on the impacts of environmental policies such as subsidies for renewable energies, emission taxes and emissions trading on energy markets.
- Empirical research on the interrelationships between European energy markets and the European emissions trading scheme.
- Presented research results at international conferences and seminars.
- Wrote policy articles and consulting papers on the implementation of emissions trading, renewable energy policy and fishery management.
- Supervised seminar thesis on different topics of environmental economics, environmental policy and competition policy.
- Gave tutorials and lectures in environmental economics, intermediate microeconomics and macroeconomics.

Past experience

2008/06 – 2010/06

Lecturer in environmental economics and policy
University of Applied Sciences Lübeck

2010/03 – 2010/05/

Guest researcher

Centre for Energy and Environmental Markets, Sydney, Australia

- Analyzed and compared the Australian and European markets and support systems for renewable energies.
- Presented research results on feed-in tariff policies and the European emissions trading market.

2005/05 – 2006/08

Student assistant

Department of Public Finance , Friedrich-Alexander-University
Erlangen-Nürnberg

2004/12 – 2005/01	<p>Intern Economic Commission for Latin America and the Caribbean (ECLAC), Santiago, Chile</p> <ul style="list-style-type: none"> ▪ Analyzed the Latin American market potential for emission reduction projects in the framework of the Clean Development Mechanism (CDM). ▪ Built a database covering existing and planned CDM projects in Latin America. ▪ Summarized the results in a report to the head of division.
2004/09 – 2004/11	<p>Intern Government of Chile, National Environmental Commission, Santiago, Chile</p> <ul style="list-style-type: none"> ▪ Worked in the environmental education program for public schools in Santiago. ▪ Cooperated with the ministry of education in organizing seminars for teachers and local authorities in environmental education.
Education	
2006/10 – present	<p>Christian-Albrechts-University Kiel Doctoral candidate (Doctoral dissertation submitted, degree expected in July 2011) Specialization: Environmental and energy economics and policy Dissertation: Analysis of carbon mitigation policies: Feed-in tariffs, energy and carbon price interactions and distortions on carbon markets.</p>
2000/10 – 2006/08	<p>Friedrich-Alexander-University Erlangen-Nürnberg Diplom-Volkswirtschaftslehre (Master of Science in economics) Master thesis: The European emissions trading scheme: Theoretical background and first practical experience.</p>
2003/03 – 2004/03	<p>University of Chile, Santiago, Chile Exchange student, Faculty of Economics and Business Administration</p>
1992/08 – 2000/06	<p>Städtisches Gymnasium Olpe Abitur (High school diploma)</p>
1997/08 – 1998/07	<p>Colegio Salesiano Benavente, Tehuacán, Mexico High school exchange student</p>
Languages and technical skills	
<p>Languages: English (fluent), Spanish (fluent), French (good command) Software: MS Office (Word, Excel, Power Point), LaTeX Programming: Mathematica, Matlab Econometric software: Eviews, Jmulti</p>	

Publications and working papers

- „Emission permits and competition“ (with Till Requate), Background paper commissioned by the Directorate for Financial and Enterprise Affairs of the Organisation for Economic Co-operation and Development (OECD), *DAF/COMP/WP2(2010)9*, 2010, 1-47.
- „Overfishing: Background and paths into a better fishery management (Überfischung: Hintergründe und Wege in ein besseres Fischereimanagement)“ (with Martin Quaas and Till Requate), *Geographische Rundschau*, 2010, 5, 48-54.
- „Environmental policy instruments in theory and practice (Umweltpolitische Instrumente in Theorie und Praxis)“ (with Till Requate), in: Johannes Varwick (Ed.): *Global Environmental Policy (Globale Umweltpolitik)*, Wochenschau Verlag, 2008, 75-96.
- „Subsidies for renewable energies in the presence of learning effects and market power“ (with Till Requate), *Kiel Working Paper No. 1689*, Kiel Institute for the World Economy, 2011.
- „An empirical model of carbon-constrained energy markets with an application to dynamic portfolio allocation“ (with Leonardo Morales-Arias), *Working Paper*, 2011.

Selected presentations

- Centre for Energy and Environmental Markets, Sydney, 2010
- End of year summit, DIW, Berlin, 2009
- European Association for Environmental and Resource Economists, Amsterdam, 2009
- Sustainable development: Demographic, energy, and inter-generational aspects, Strasbourg, 2008

June 1, 2011