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CO2 emissions trading in the EU

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2016

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Mulder, A. J. (2016). *CO2 emissions trading in the EU: Models and policy applications*. [Thesis fully internal (DIV), University of Groningen]. University of Groningen.

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Download date: 21-04-2025

CO$_2$ Emissions Trading in the EU: Models and Policy Applications

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Publisher: University of Groningen
Groningen, the Netherlands

Printed by: Ipskamp Drukkers B.V.

ISBN: 978-90-367-8517-4

eISBN: 978-90-367-8516-7

CO2 Emissions Trading in the EU

Models and Policy Applications

PhD thesis

to obtain the degree of PhD at the
University of Groningen
on the authority of the
Rector Magnificus Prof. E. Sterken
and in accordance with
the decision by the College of Deans.

This thesis will be defended in public on

Thursday 4 February 2016 at 12.45 hours

by

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To my parents

ACKNOWLEDGEMENTS

Over the past four years, many people have helped me to complete this thesis.

First of all, I would like to thank my supervisors, Catrinus Jepma, Erik Dietzenbacher and Steven Brakman. I’m very thankful for your trust, expertise, patience and support. Catrinus, thank you for introducing me to the topic of CO_2 emissions trading, for all of the inspiring discussions and the great opportunities you have given me. Erik, thank you for the many hours you have invested to eliminate inaccuracies. Your work has greatly improved the quality of this thesis. Steven, thank you for your support and thought provoking insights over the past years.

I’m also greatly indebted to Christian Bos who encouraged me to pursue the PhD while I wrote my Master thesis at TNO. Also, thanks to Leo Hoenders for introducing me at TNO in the first place. Bas Jongerius, Chris Hendriks and Pieter van Breevoort, thanks for your help and input in the early stages of the model development.

Over the past years I have had the pleasure to meet many inspiring colleagues, in and around the faculty building. Hengki, Klaas, Ines and Lisa, thanks for your enjoyable company as my office mates. Hengki, thanks for your introduction to Indonesian culture and its warm and welcoming people. Igor, thank you for the great fun and laughter. Also, your football skills require mentioning because you helped our team out when we were one man short in an official match. Because of our clear lack of talent, you luckily had no trouble whatsoever to become an instant added value. Reitze, Dominic, Maaike, Tristan, Gaaitzen and Klaas, thanks for the fun conversations over coffee and lunch. Last, but definitely not least, I would like to thank the Gemmies Jenny, Herma, Sylvia and Linda for their support and pepernoten.

ONR 4, the low-quality high-enthusiasm football team I played in, also deserved my gratitude. Despite our many losses and lack of trophies, the enthusiasm and team spirit more than compensated for that. It was a great source of energy for me. My friends on the race bike also provided a great source of energy and inspiration. Ruurd, Fred and Niels, thanks for the Marmotte experience.

Boy, Jord, Henk, Thijs, Ewoud, Niels, Lennart, Jasper and Sten. May our friendship grow stronger every year. Thanks for many great memories so far! Jord, thanks for your introduction at ABN AMRO, and thanks to all my new colleagues for their warm welcome! Also, I would also like to thank Willem, Nico, Rineke, Gijsje, Jules, Michiel, Anne-Roos and Stefanie for their friendship, kindness and support.

I would like to thank my family for their everlasting faith in me. Most of all, I owe great respect and thanks to my parents who taught me early on to persevere in whatever I would choose to pursue. Infinite thanks for your continuous loving support. Martin and Annelie, thanks for simply being a great big brother and sister in law. Donka, thank you for being a loving mother in law and grandmother to Max and Daan. Nicolai, thanks you for your warm welcome, help and advice.

Finally, I want to thank the love of my life, Boyana. We met in the first months of my PhD because I temporarily had an office on your department. By now, we're engaged, have two children and live on the other side of the country. I can safely say that my PhD could not have been more productive. Neither could I have been luckier and happier than I am with you, and our two kids. Max and Daan, you guys are an endless source of love, joy and energy. Thank you so much.

Arnold

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1. INTRODUCTION

1.1. The rise (and fall?) of CO_2 emissions trading schemes

The Rio Conference in 1992 is generally considered to be the start of a global effort to combat atmospheric climate change. A total of 172 governments participated in the conference that was held in Rio de Janeiro. A key result of the conference was that the UNFCCC (United Nations Framework Convention on Climate Change) treaty was agreed upon. The treaty had the objective to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Specific limits on GHGs were not mentioned in the treaty, but it provided a framework for further negotiations. The parties to the UNFCCC returned to the negotiation table a total of 20 times between 1995 and 2004 at so-called Conferences of Parties. Despite those years of negotiations and growing evidence for the human role in atmospheric climate change (IPCC, 1990, 2007, 2013), there is currently no effective worldwide agreement on either a target or an instrument to curb GHG emissions.

The Kyoto Protocol came closest to being a comprehensive set of legally binding targets for GHG reduction. The protocol stipulated GHG reduction targets for 41 nations, to be achieved by 2012. For most other parties to the UNFCCC no reduction target was set because they were considered to be developing countries. The United States of America (USA) refused to ratify the Kyoto Protocol and, as such, had no legally binding reduction target. As the end of 2012 neared, the negotiations over a renewed commitment period beyond 2012 proved difficult. Large emitters like the USA, Russia and China did not commit to reduction targets while many other countries wanted to hold on to their status as developing country. Finally, after lengthy negotiations, a renewed less ambitious commitment until 2020 was agreed upon, with fewer nations backing the commitment. However, based on the process over the last 20 years, a truly global effort to combat atmospheric climate change is not likely to be reached easily if at all.

Throughout the negotiation process, the European Union (EU) remained a strong supporter of stringent global GHG emission reduction targets. The stance of the EU was no surprise. In fact, the Maastricht Treaty, which was signed in 1992 by all EU member states, included the objective that EU policy on the environment should contribute to the promotion of measures at the international level to deal with regional or worldwide environmental problems (Sbragia, 1998).

In absence of a unified global effort, the EU chose to lead by example by introducing ambitious energy and climate related targets in 2009. The objectives, known as the “20-20-20” targets, were to reduce CO_2 emissions (-20%), increase the share of renewables (+20%) and improve energy efficiency (+20%) in Europe by 2020.

As a means to achieve the CO_2 emissions reduction target, the EU pioneered the introduction of a CO_2 emissions trading scheme in 2005. The scheme is officially called the European Union Emissions Trading Scheme (EU ETS) and is considered to be Europe’s flagship instrument in its efforts to curb GHG emissions (Delbeke, 2006; Convery, 2009). The scheme caps the CO_2 emissions of a large range of energy-intensive sectors, including the electricity, steel, oil, gas and cement sectors across Europe. Although emissions trading schemes had been introduced before in Europe and elsewhere to combat SO_X and NO_X emissions, the EU ETS was the first emission trading scheme focussed on CO_2 emission reduction.

The leading example of the EU gathered a following, as currently 14 other ETSs have been launched around the world. Also, 3 ETSs are scheduled to be launched and 14 others are currently considered (ICAP, 2014). Cumulatively, all 15 operational ETSs now cover approximately 9% of the annual global anthropogenic (*i.e.* man-made) CO_2 emissions (World Bank, 2014). The EU ETS remains by far the largest ETS in the world. For an overview of all ETSs that were operational in 2014, see Box 1.

Although Europe has successfully taken a leading role in the combat to curb GHG emissions (Schreurs and Tiberghien, 2007), the performance of the EU ETS has fallen far below prior expectations of legislators and others. In 2008, three and a half years after its introduction, the EU ETS carbon price peaked at around €35. Since then, the price has fallen to levels below €3 in early 2013. The European Commission (EC, 2013, 2014a) noted that the EU ETS is currently too weak to seriously incentivize investments in CO_2 abatement technologies. The weak performance of Europe's flagship instrument undermines Europe's leading role in the effort to curb GHG emissions and may halt the, so far, growing popularity of emission trading schemes around the world.

In line with its pro-active stance towards GHG abatement, the European Commission has voiced its ambition to introduce measures to improve the performance of the EU ETS. In fact, without a credible incentive for investments in CO_2 abatement technologies in the short and medium term, the European Commission expects that it will become harder to reach long-term CO_2 emission reduction targets in a cost-effective manner (EC, 2014a).

The position of the European Commission points to multiple policy objectives. Apart from the objective to cap emissions of energy intensive sectors below a target level, which the EU has already accomplished by introducing the EU ETS, the European Commission is also concerned about the dynamic efficiency of the EU ETS. Dynamic efficiency of the EU ETS refers to its impact on the rate of investment in CO_2 abatement technology over time. If the investment rate is low for a long time, infrastructure for and experience with the deployment of abatement technology is not developed, both of which have the potential to reduce the

Box 1: Emissions trading around the world in 2014

15 ETSs are currently in force around the globe. An overview, including all data sources, is provided in the table below. Note that the EU ETS is by far the largest ETS, covering 1,925 $MtCO_2$, which is equal to 45% of all anthropogenic CO_2 emissions in the participating nations. The remaining 55% is emitted by sectors that fall outside the scope of the EU ETS, such as households, small businesses, forestry, road transport, buildings, waste handling and agriculture.

Note that other GHGs, such as N_2O and CH_4, are also often included in the schemes. Compared to CO_2, the emission level of these other gasses is relatively small in absolute terms ($MtCO_2$), although their role with respect to climate change cannot be neglected. CO_2 emissions are responsible for approximately 77% of anthropogenic climate change, while CH_4 (14%) and N_2O (8%) play smaller yet significant roles as well (IPCC, 2007). As the table shows, ETSs are currently primarily geared towards reducing CO_2 emissions.

Table 1.1: Overview of ETSs that are currently in force

Scheme	Coverage in $MtCO_2$	Coverage in % of total CO_2 emission in region	Coverage of sectors								Coverage of other GHG		Carbon price in €/tCO_2*
			Electricity	Industry	Forestry	Aviation	Transport	Buildings	Waste	Agriculture	N_2O & PFCS	CH_4 & HFC	
EU ETS	1,925	45	X	X		X					X		8
New Zealand	38	50		X	X		X		X		X	X	1
RGGI	91	20	X										3
Tokyo	14	20						X					82
Switzerland	5	10	X					X			X		19
California	161	35	X	X							X	X	10
Quebec	23	30	X	X							X	X	9
Kazakhstan	142	50	X	X			X			X			1
Shenzhen	58	38	X	X				X					10
Shanghai	149	50		X		X	X						4
Beijing	94	50	X	X				X					8
Guangdong	256	42	X	X									9
Tianjin	129	60	X	X				X					3
Chongqing	92	38	X										3
Hubei	162	35	X	X									3

Sources: ICAP, 2014; World Bank, 2014; *Rounded price in 2014, Kazakhstanian price level taken from www.tbc.kz.

The ETSs are scattered around the globe geographically. Two are located in the United States of America (California and the RGGI). The RGGI is a cooperative scheme between nine states in the USA (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont). Seven schemes are located in China (Shenzhen, Shanghai, Beijing, Guangdong, Tianjin, Chongqing and Hubei), while Canada (in Quebec), Kazakhstan, Switzerland and Japan (in Tokyo) also govern an ETS.

China has voiced the ambition to introduce a national ETS (Reuters, 2014). In preparation to such a national scheme, China considers its seven city-level ETSs as pilot programs. If a national ETS is introduced in China, its size (in $MtCO_2$ of covered emissions) is likely to easily surpass the size of the EU ETS. Total CO_2 emissions in China were estimated at 10,300 $MtCO_2$ in 2013 (PBL, 2014). Assuming that a national Chinese ETS would have an equally large coverage of the EU ETS (45% of total CO_2 emissions), the Chinese ETS would be 2.4 times as large as the EU ETS.

The sectors that are most frequently covered by an ETS are the electricity sector and the industry. These sectors are particularly well suited for an ETS because they consist out of large stationary sources of CO_2. The large and stationary nature of emitters implies that monitoring and abatement of CO_2 emissions is relatively easy. The sectoral category Industry typically refers to CO_2 emitting installations in the oil, gas, cement, iron, steel and paper industry (although not all of them are covered by each ETS that is said to cover the industry in Table 1.1).

In the final column of Table 1.1 the rounded level of the ETS-driven market price in 2014 is shown. The observed prices are all at or below €10, with the exchanges of Tokyo (€82) and Switzerland (€19) as notable exceptions. The high CO_2 price in Tokyo is partly explained by illiquidity in the market. Because few allowances are traded, the price does not necessarily reflect the economic fundamentals of that market. This reasoning also holds for the Swiss ETS (€19) as it is a rather minute and, thereby, illiquid market. Policymakers in the EU and Switzerland are looking at the possibility to link the Swiss ETS to the EU ETS. In that event, the Swiss market would become much more liquid, allowing the price to converge with the CO_2 price of the EU ETS. However, so far, no agreement has been reached.

abatement costs of technologies (Wright, 1936; Rapping, 1965; Duke and Kammen, 1999; Grübler *et al.*, 1999; Junginger *et al.*, 2010). Reduced abatement costs usually imply that the long-term emission reduction target can be reached at a lower societal cost. Therefore, the European Commission also wants to ensure that the EU ETS continuously provides a credible incentive for investments in CO_2 abatement technologies in Europe. So far, this second objective has not been achieved.

EU legislators now face the difficult task to design and find political consensus for measures that can revitalize the EU ETS. Finding political consensus is a complicated task given the large geographical and sectoral scope of the EU ETS, and the large number of (often conflicting) interests that stakeholders may have. Against this background, it is crucial for policymakers to have a deep understanding of the drivers behind the performance of the EU ETS. Such understanding, for that matter, is valuable for both policymakers in Europe, as well as legislators around the world that are governing or considering the introduction of an ETS.

The analysis in this research project is intended to provide that deeper understanding regarding the performance drivers of the EU ETS. We zoom in on CO_2 emissions trading within the EU ETS[1] and develop a dynamic stochastic simulation model to uncover which factors drive the performance of the EU ETS. Also, we examine which policy responses are best suited to improve its performance.

In Section 1.2 of this introduction we explain the key principles and mechanisms through which an ETS operates to reduce CO_2 emissions. In Section 1.3, we examine the performance of the EU ETS so far in more detail. Subsequently, in Section 1.4, we present the research questions of this thesis. Finally, in Sections 1.5–1.8 provide overviews of Chapters 2-5 respectively.

1.2. CO_2 emissions trading: internalizing an externality

An ETS is an instrument that, via trade in emission allowances, puts a price tag on the act of emitting CO_2 into the atmosphere.[2] By putting a price tag on emitting CO_2, an ETS forces firms and other economic agents to take CO_2 emissions into account while making operational and investment decisions. In absence of a price tag, emitting CO_2 is free, while

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[1] As shown in Table 1.1, current ETSs are mainly geared towards reducing CO_2 emissions, although other GHG gasses are also to some extent covered by the ETSs that are currently in force. In the remainder of this thesis, we focus exclusively on CO_2 emissions trading and ignore other GHGs. Because the analysis of climatic effects is outside the scope of this thesis and because the volume of other GHG gasses is relatively small in absolute terms, this simplification can be made without a significant loss of detail.

[2] The description in this section is equally valid for other GHGs, but, in line with the rest of the thesis, we focus exclusively on CO_2 emissions.

society at large does face the potential dangers of anthropogenic climate change. These dangers include rising sea levels and intensified extreme weather conditions, such as floodings, hurricanes and/or extreme drought (IPCC, 1990, 2007, 2013).

In economic terms, an ETS internalizes an externality (Freeman *et al.*, 1992). The externality is the cost that the society faces from anthropogenic CO_2 emissions. The externality is internalized into the decision making of firms and other economic agents via the costs that are incurred to obtain emission allowances.

The construction of an ETS can be divided into three steps: setting a cap on emissions, choosing an allowance allocation mechanism and, finally, enabling trade in emission allowances. Each of these steps will now be discussed on more detail.

First, legislators have to set a cap on emissions. European legislators have set a reduction target for energy intensive sectors of -21% for 2020, compared to the reference year 2005. In line with this target, the overall cap (*i.e.* the total number of emission allowances that was to be distributed) was determined. A single EU ETS emission allowance provides the holder with the right to emit one metric tonne of CO_2 into the atmosphere. In turn, emitters have to surrender (*i.e.* hand in) an allowance for every tonne of CO_2 that they emit. If a firm fails to surrender an allowance for a tonne of CO_2 that is emitted, a high fine is incurred. By reducing the number of allowances that are issued over time, the EU ultimately forces firms to reduce their emissions, in line with the emission reduction target.

Second, legislators have to decide how to allocate the emission allowances to emitters. EU legislators use three allocation mechanisms: grandfathering, benchmarking and auctioning. Under grandfathering, allowances are allocated free of charge to emitters based on their historic emission level. Grandfathering was used until 2012 as the EU ETS allocation mechanism. Starting in 2013, the EU switched to free allocation via benchmarking. Under benchmarking, the amount that is allocated to an emitter is based on a product-level performance benchmark. A product-level performance benchmark reflects the average CO_2 emissions output of the 10% best performing installations in the EU to produce a specific product. Emitters with outdated production technology thus do not receive sufficient free allowances to cover their emission output, while best-of-class installations receive (more than) full compensation for free. In this manner, the allocation mechanism rewards efficient technology. Parallel to the introduction of benchmarking, auctions have also been introduced in 2013. On auctions, allowances are sold to the highest bidder. The auction revenue goes to the member-state governments in the EU. Whether a sector can obtain allowances for free via benchmarking, or has to pay for allowances via auctioning, depends on the extent to which an ETS sector faces international competition from countries without comparable climate legislation. The greater the international competition, the greater the proportion of allowances that are allocated for free. In that manner, the allocation mechanism minimizes the distorting impact of the EU ETS on the international level-playing-field.

Finally, once allowances are allocated, emission allowances can be traded via exchanges. Firms that hold more allowances than they require to cover their emissions, are allowed to sell them to other firms that do not have sufficient allowances to cover theirs. Also, via trade, firms that lack low-cost options to reduce their own emission level can buy emission allowances from other firms that do have low cost CO_2 abatement opportunities available. In this manner, at least theoretically, the market-based approach ensures that the emission reduction target may be met while the lowest-cost CO_2 abatement opportunities are utilized to do so.

Note that an ETS does not necessarily internalize all of the costs that are associated to the climate change externality. The extent to which the costs of the externality are reflected in the CO_2 price depends in part on the emission reduction target that is set by the governing authority. The more ambitious the emission reduction target, the less allowances are distributed, the higher the CO_2 price, and the more costs are internalized by firms under the ETS.

1.3. The EU ETS: origins and performance so far

Initially, in line with its tradition, the European Union was mainly focussed on regulatory approaches to curb CO_2 emissions, as opposed to market-based approaches such as the ETS. The EU gradually changed its stance towards a market-based approach and became a CO_2 emissions trading pioneer. However, so far, the performance of the EU ETS has fallen far below prior expectations.

In 1991, the Environment Commissioner of the European Commission, Carlo Ripa di Meana, announced a proposal to introduce a combination of a tax on the CO_2 content of fuels, and a tax on all non-renewable forms of energy (notably nuclear power). The two components would be combined in equal proportions. For example, half of the tax on a barrel of oil would be related to its carbon content and half to the energy component. The tax was intended to be introduced in stages, starting in 1993. The initial level was intended to be \$3 per barrel of oil and would then be increased by \$1 annually to reach a level of \$10 in 2000 (EC, 1991; Pearson and Smith, 1991).

The proposal was eventually rejected, mainly due to opposition by the United Kingdom. To this day, introduction of a tax at the European level remains controversial because fiscal policy is often considered to be the responsibility of individual member states within the EU. After the proposal was rejected, the European Commission encouraged individual member states to introduce national taxes on a product-by-product basis (EC, 1996).

The EU advocated a norm where domestic policy changes were considered as the only legitimate mechanism to reduce domestic emissions (Cass, 2005). During the Kyoto negotiations in 1997, the USA pushed for the adoption of international emissions trading. The EU was suspicious of that idea, seeing it as an illegitimate manner to avoid domestic responsibilities. The eventual compromise text of the Kyoto Protocol did include the possibility of creating an international emissions trading system[3] that would come into force in 2008 (Cass, 2005). In the years following the signing of the Kyoto Protocol, the European Commission repeatedly pointed out that ' … the best preparation for the Community and its member states might be to develop their own emission trading experience (EC, 1998, 1999, 2000). The EU fully adopted emissions trading by passing two directives (EC, 2003, 2004). The directives outlined the design of the EU ETS as it would become operational on the 1st of January 2005.

Clearly, the stance of the EU had changed. This change is generally attributed to a process of policy learning that drew from experiences of the USA in its Acid Rain Program (Damro and Luaces-Mendes, 2003; Damro *et al.*, 2008; Cass, 2005). In the Acid Rain Program, the USA has successfully implemented an emissions trading scheme to curb SO_X emissions, a major precursor of acid rain (Ellerman *et al.*, 2000).

Several other factors played a role in the popularization of an ETS. First, an ETS accommodated to the need of international organizations and business lobbies (Damro and Luaces-Mendes, 2003). Businesses generally favoured emissions trading over regulatory

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[3] The Kyoto emissions trading scheme is fundamentally different from the EU ETS. Under the Kyoto emissions trading scheme allowances can be earned after emission reduction has been achieved on a project basis. The earned allowances can subsequently be traded and/or used to offset emissions. The Kyoto emissions trading scheme thus awards investments in CO_2 abatement technology, while anyone that meets a set of regulatory requirements can apply to receive the allowance. In contrast, the EU ETS penalizes the emissions of a specific group of emitters.

approached because emissions trading would create a tradable asset, while a tax would extract revenue from firms without adding any compensating value (Grubb *et al.*, 1999). Secondly, a pan-European ETS would create a level playing field within the EU in line with its internal market objective (Convery, 2009). Thirdly, an ETS would still allow the EU to commit to strong emission reduction targets. Finally, an ETS can accommodate to stark differences between individual member-states within the EU via its allowance allocation mechanism.

These differences between member-states are best illustrated by the EU burden-sharing agreement that was agreed upon in 1996. The burden-sharing agreement is shown in Table 1.2 and answers the question of "who should do what" within the EU to reach its Kyoto commitment. By taking into account the concerns of individual member states, each member state was assigned a reduction target, such that the overall Kyoto reduction target of 8% would be achieved in 2012. This differentiation was made for various reasons, among them emission objectives of member-states, special treatment of cohesion countries,[4] economic restructuring (particularly in Germany and the UK) and national policies in energy and industrial sectors (Damro and Luaces-Mendes, 2003).

Table 1.2: Burden sharing in the EU

Member state	**% share of EU GHG emissions in 1990**	**% reduction target in 2012 compared to 1990**
Austria	1.7	-13.0
Belgium	3.2	-7.5
Denmark	1.7	-21.0
Finland	1.7	0.0
France	14.7	0.0
Germany	27.7	-21.0
Greece	2.4	+25.0
Ireland	1.3	+13.0
Italy	12.5	-6.5
Luxembourg	0.3	-28.0
Netherlands	4.8	-6.0
Portugal	1.6	+27.0
Spain	7.0	+15.0
Sweden	1.6	+4.0
United Kingdom	17.9	-12.5
Total	*100.0*	*-8.0*

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[4] Cohesion Countries are EU member states whose per capita gross national income is less than 90 % of the EU average.

To divide the overall EU ETS allowance cap between the member states, the burden-sharing agreement was an important input (*i.e.* member states with more stringent reduction targets were awarded relatively less emission allowances).

The precise member state cap and manner of allocation was described in a National Allocation Plan (NAP) that was drafted by each member state (member states were also forced to keep registers to monitor, verify and report on the compliance of emitters). Three months after delivery of a NAP to the European Commission, the commission would reject (in which case the NAP would have to be revised) or accept it (EC, 2003). Acceptance or rejection depended to a large extent on whether the reported emission and allocation levels in the NAP were in line with the projected emission levels in reality. Despite this procedure, and because projecting the real emission level before the launch of the EU ETS was difficult, the accepted NAPs led to allowance allocation levels that were significantly above the eventual emission levels in the first operational years of the EU ETS. However, in the design of the EU ETS, legislators had accounted for the possibility of unforeseen issues by designating Phase I of the EU ETS (2005-2007) as a trial period. The trial period allowed legislators to introduce amendments to the EU ETS Directives and NAPs, and thereby start Phase II (in 2008) with an improved design and adjusted allowance supply levels.

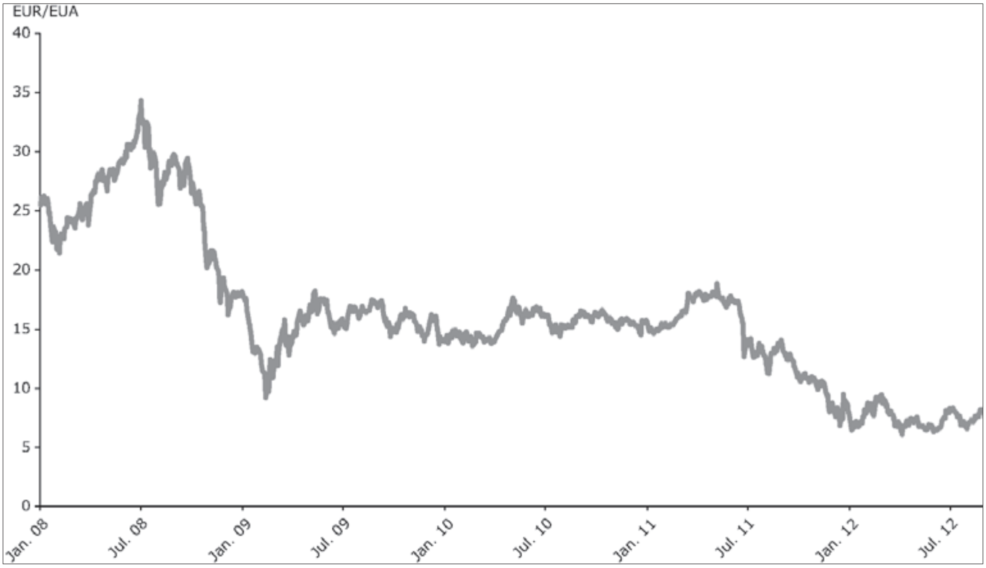
One of the crucial differences between Phase I (2005-2007) and Phase II (2008-2012) was that banking of allowances was first allowed in Phase II. Previously, in Phase I, allowances that were allocated in a specific year could not be transferred to the next year. Allowances thus effectively had an expiration date, and consequently, their value would gradually fall to €0 as the expiration date neared. Starting in 2008 allowances no longer had an expiration date and would thus keep their value. This improved the tradability of allowances, but also meant that surpluses of allowances now had the potential to build up over time.

Shortly after the start of Phase II of the EU ETS in 2008, an economic downturn lead to a 11.6% fall in the emission level of emitters under the EU ETS (EC, 2010). Reinforced by the ability to bank emission allowances, the price of EU ETS emission allowances (officially termed European Union Allowances, or EUA) took a strong hit, falling from approximately €35 in July 2008 to around €8 in early 2009 (see Figure 1.1).

The EU ETS carbon price never recovered to the price levels that were witnessed in the first year of Phase II, and even fell below €3 in early 2013. Whereas European industry officials were initially concerned that the CO_2 price would become too high, undermining their competitiveness in international markets (Grubb and Neuhoff, 2006), European legislators are now primarily concerned that the CO_2 price is too low to have a meaningful impact on operational and investment decisions within the industry (EC, 2013, 2014a).

In the remainder of this research the terms CO_2 price, EUA price, allowance price and

Figure 1.1: Historical price of EUAs in € per allowance from January 2008 to July 2012



Source: European Environmental Agency, http://www.eea.europa.eu/data-and-maps/figures/eua-future-prices-200820132012. Note that the EUA price has fluctuated between approximately €3 and €7 since July 2012 until early 2015, http://www.eex.com.

carbon price will be used interchangeably to refer to the EU ETS-based EUA price per metric tonne of CO_2, unless specifically stated otherwise.

Currently, the EU ETS is in Phase III (2013-2020), with Phase IV starting in 2021. Significant structural changes to its design could therefore be implemented now, but would most likely enter into effect at the start of Phase IV at the earliest. With several years remaining until then, this leaves some room to design policies that could help to reach the dynamic efficiency objective of European legislators. The key question that remains is which type of amendments is most effective to obtain a credible incentive for investment in CO_2 abatement technology via the EU ETS. In this thesis, we intend to provide a deeper insight into the performance drivers of the EU ETS. Those insights could ultimately assist policymakers to bring the performance of the EU ETS in line with the policy objectives of the EU.

1.4. Analysing the performance drivers of the EU ETS

In this thesis, we examine the performance drivers of the EU ETS. Specifically, we zoom in on two relevant issues and their associated streams of literature:

1) To what extent do potential investors in a set of abatement technologies called Carbon Capture and Storage (CCS) face extra investment uncertainty when they are forced to comply with the EU ETS and dependent on a volatile allowance price to have a profitable business case? We focus on CCS because its large scale deployment is often considered to be among the most critical solutions to reach stringent CO_2 emission reduction targets towards 2050 (Pacala and Socolow, 2004; IPCC, 2005; Haszeldine, 2009; EC, 2009b; IEA, 2010, 2011). So, if potential investors in CCS face

too much investment uncertainty under the EU ETS, the deployment of a potentially critical abatement technology is unlikely to materialize;

2) To what extent is the impact of the EU ETS on investment behaviour affected by the interaction with other climate and energy related instruments that are currently in place around Europe? In recent years, EU member states have introduced a large number of instruments alongside the EU ETS that also, directly or indirectly, are meant to affect the CO_2 emission level (EEA, 2011a; Lundberg *et al.*, 2012; IPCC, 2013). Examples are instruments that promote the use of renewable electricity generation technologies or energy efficiency measures. Many of these instruments tend to depreciate the EU ETS allowance price (Interact, 2003; Harrison *et al.*, 2005; Sorrell *et al.*, 2009; Alberola, 2014) and therefore may be an important driver behind the regularly observed low allowance prices. In that manner, instruments that operate in parallel to the EU ETS may strongly influence investment behaviour around Europe and, thereby, the dynamic efficiency of the EU ETS. So far, however, it has remained unclear how large the role of such adverse policy interaction between the EU ETS and other instruments has been exactly.

Both themes, the investment potential for CCS under the EU ETS (*e.g.* Stangeland 2007; Odenberger *et al.*, 2008; Broek *et al.*, 2010; Odenberger and Johnsson, 2010; Broek *et al.*, 2011; IEA, 2011; Strachan *et al.*, 2011), as well as the interactions of the EU ETS with other instruments (*e.g.* Conrad and Kohn, 1996; Morthorst, 2001, 2003; Amundsen and Mortensen, 2001; Jensen and Skytte, 2003; Hindsberger *et al.*, 2003; Rathmann, 2007; Del Rio, 2009), have been confronted in the academic literature before. However, we argue that these issues have been inadequately dealt with because (1) the ETS is often superficially modelled, to the extent that it operates as either a *de-facto* CO_2 tax or as a simple annual emission quota (disregarding the ability of firms to bank allowances), and (2) because the essential element of stochastics (*i.e.* uncertainty) is missing. Existing modelling efforts therefore do not accurately reflect the dynamic design and functioning of the EU ETS. Assessing the performance of the EU ETS on the basis of such methods may therefore lead to inaccurate or even biased results.

To assess the impact of the EU ETS on investment behaviour, key design elements of the EU ETS are inputs to our model (notably the supply of allowances, the stochastic nature of the demand for allowances and the ability to bank allowances); the CO_2 price is an endogenous model variable, and investment levels in CO_2 abatement technologies are model output. In this manner, we are able to assess to what extent the existing design of the EU ETS will enable investments in abatement technologies over time. On top of that, we test the impact of amendments to the EU ETS Directive on the CO_2 price and investment levels.

Because the demand for allowances is modelled stochastically, the CO_2 price exhibits a volatile pattern over time in our model. The volatile nature of the CO_2 price is also represented in existing literature. However, this is often done by exogenously generating a stochastic CO_2 price via a Geometric Brownian Motion (GBM). This approach can be extremely useful to determine, among others, at which level of the CO_2 price a technology is expected to become a profitable investment option (EPRI, 1999; Rothwell, 2006; Laurikka and Koljonen, 2006; Blyth *et al.*, 2007). However, because this approach relies on an exogenously determined allowance price (which is not linked to the supply, demand and banking of emission allowances) these existing studies do not reveal whether the current, or amended, design of the ETS will drive such investments.

Our approach does enable us to answer these questions, related to the dynamic efficiency of the current EU ETS design. To see why the explicit modelling of the allowance supply regime, the banking provision and stochastic demand patterns are so important when examining investment rates via the EU ETS, consider a downward demand shock that leads to the build-up of a stock of banked allowances. Once a stock of allowances has formed, it may take years or even decades before the stock is depleted, and its depreciating effect on the CO_2 price has disappeared. The combination of uncertain allowance demand and the banking provision can thereby lead to pathways regarding the level of the CO_2 price and thus the investment behaviour of firms that strongly diverge from policy expectations and intentions. Static and deterministic models do not capture these pathways. In this thesis, we do capture these pathways because we employ stochastics over a simulation window that runs from 2008 to 2030. Finally, our stochastic approach has the advantage over traditional approaches that a direct link can be established between a specific design of the EU ETS and the likelihood of a specific outcome. This means that we can provide probability distributions for each of the variables that are endogenous to, or output of, the model.

In the next four sections of this introduction, we provide extended summaries of Chapters 2, 3, 4 and 5. In the remainder of this section, we provide a very brief overview of those chapters. In Chapter 2 we develop a dynamic stochastic simulation model of the EU ETS and assess to what extent potential investors in CCS face extra investment uncertainty via the EU ETS allowance price. We test to what extent amendments to the design of the EU ETS affect the potential for and uncertainty of investments in CCS. The results can help policymakers to develop a more goal-oriented policy design, specifically in light of the concerns regarding the dynamic efficiency of the EU ETS (EC, 2013, 2014a). In Chapters 3 and 4, we apply the dynamic stochastic simulation model to more complex policy settings.

Specifically, in Chapter 3, we test under which circumstances the EU ETS could become redundant under the influence of instruments that operate in parallel to the EU ETS and adversely affect the ability of the EU ETS to incentivize investments in CO_2 abatement technologies. We distinguish between two different classes of parallel instruments and assess which type of parallel instrument undermines the performance of the EU ETS the most. The analysis can help policymakers to weigh more accurately the potential costs that are involved when introducing parallel instruments, *i.e.* in terms of reduced strength of the EU ETS incentive. The insights may be used to eventually introduce measures that ensure that the impact of the EU ETS on investment behaviour cannot be marginalized due to such parallel instruments. In Chapter 4, we perform a detailed case study on policy interaction between the EU ETS and two parallel instruments in the German power sector to better understand to what extent the current ETS carbon price is influenced by specific instruments that are currently in force. To perform the analysis, the dynamic stochastic simulation model of the EU ETS is extended with a module that captures the German power sector and the two German parallel instruments in a detailed manner. Both the development of this model extension and its application are covered in Chapter 4. The case study shows to what extent the current performance of the EU ETS is undermined by these two instruments in the German power sector. The results show that the combined impact of two German parallel instruments on the performance of the EU ETS is significant and suggest that parallel instruments across the whole of Europe are to a large extent responsible for the currently observed weak performance of the EU ETS. The study provides direction for policymakers interested in stimulating the influence of the EU ETS on abatement activity with or without amendments to the design of the EU ETS itself.

1.5. Chapter 2 – Stochastic simulation of CO_2 emissions trading in Europe: will the EU ETS drive investments in CCS?

In Chapter 2, we examine the investment potential under the EU ETS for the set of CO_2 abatement technologies that is known under their collective name as Carbon Capture and Storage (CCS). The characteristic that all types of CCS share is that they enable operators in energy intensive sectors to separate CO_2 from other waste gasses and to safely transport it to a storage facility. Such a storage facility is typically an empty gas reservoir or saline aquiver in the deep underground.

Apart from a few demonstration projects, CCS is currently not deployed on a commercial scale. Studies do show, however, that CCS offers a large technical potential for CO_2 abatement. Pacala and Socolow (2004) argue that CCS has the potential to account for 1/7th of the required global abatement efforts necessary to prevent the most devastating consequences of anthropogenic climate change. The deployment of CCS could, in fact, be critical in order to be able to reach deep emission cuts towards 2050 (IPCC, 2005; Metz and de Coninck, 2007; EC, 2009b; IEA, 2010, 2011). More importantly, if CCS is deployed in a timely and structural manner, its deployment cost can decrease significantly. Thereby, CCS can not only contribute substantially to achieving long-term emission targets, but it also does so at substantially lower cost compared to a scenario without CCS (*e.g.* Finnon, 2012; Riahi *et al.*, 2004). The question that remains is whether the EU ETS will be able to offer an economic incentive that is strong and stable enough to structurally drive the deployment of CCS.

If the carbon price is sufficiently high and stable, CCS projects can materialize, whereas the deployment and development of CCS may come to a standstill if the carbon price remains low and/or is volatile. Even is CCS becomes economically viable, other factors, that we have not explicitly modelled, may still block the deployment of CCS. Such factors include societal acceptance (Alphen *et al.*, 2007; Huijts *et al.*, 2007) policy, technological or infrastructural obstacles (Stigson *et al.*, 2012). Nevertheless, economic viability is a minimum requirement for deployment to occur. We test how the current design of the EU ETS, as well as some amendments to its design, affect the economic scope for deployment of different types of CCS until 2030.

In the context of the EU ETS, macro-economic growth uncertainty may translate into significant investment uncertainty for investors in CCS. If the economic growth rate remains below the historic average until 2030, very little investments in CO_2 abatement technology may be required to remain below the EU ETS allowance cap. The relatively sluggish economy will lead to a relatively low production and CO_2 emission level, making additional investment in CO_2 abatement technologies less necessary. Alternatively, if the economic growth rate is above the historic average until 2030, the rising production levels add to the existing need to invest in CO_2 abatement technologies, possibly providing sufficient support for significant deployment of CCS.

Operators of other technologies than CCS will equally be confronted with this type of investment uncertainty, but CCS provides a particularly relevant case given its large capital expenditure requirements, long lead-times and its potentially crucial role towards achieving long-term emission reduction goals.

We perform a Monte Carlo analysis with our newly developed simulation model of the EU ETS in which the allowance price is an endogenous model parameter. We account for macro-economic growth uncertainty by stochastically sampling the annual growth rate of the business-as-usual CO_2 emission level of EU ETS sectors (emissions in non-EU ETS sectors are outside the scope of this research). We take into account that firms across Europe pursue different allowance banking strategies given that they have imperfect foresight, and heterogeneous investment opportunities.

Our findings suggest that the EU ETS incentive is too unpredictable to drive the deployment of CCS in a structural manner. Under current regulation, the total scope for CCS technologies is forecasted to average around 85 MtCO$_2$/yr by 2030 based on their average deployment costs, with a standard deviation of 70 MtCO$_2$/yr. The standard deviation around the scope for CCS is not reduced, and may even increase, if the allowance supply is restricted. This suggests that allowance supply restrictions are unlikely to enable investments in CCS on the basis of the EU ETS allowance price alone. If policymakers are interested in strengthening the EU ETS, to the extent that it may drive investments in technologies with such high lead times and capital requirements, amendments to the EU ETS Directive should aim at reducing the uncertainty of the allowance price.

1.6. Chapter 3 – Interaction between EU instruments and member-state instruments: the end of CO$_2$ emissions trading in Europe?

In this chapter, we introduce the reader to the strand of literature that examines policy interaction between emission trading schemes and instruments that are introduced in parallel to such schemes. Alongside the EU ETS, many other parallel instruments have been introduced which are also meant to affects the CO$_2$ emission level. Thereby, however, they also interact with the impact of the EU ETS on the emission level and investment behaviour. Notable examples of parallel instruments are feed-in tariffs that stimulate the deployment of renewables, or subsidies/mandates for biomass co-firing. Yet many other instruments are deployed at the international, national, regional and local level.

Parallel instruments can have benefits for the national government that introduces the instrument, such as employment benefits or stability of electricity supply (Sorrell and Sijm, 2003; Bennear and Stavins, 2007). However, with respect to CO_2 abatement, parallel instruments are direct substitutes for the EU ETS. The abatement achieved through parallel instruments generally reduces the demand for EU ETS emission allowances (either directly or indirectly) and lowers the CO_2 price. The lowered CO_2 price subsequently reduces the amount of abatement that is triggered elsewhere in Europe via the EU ETS. Building on this logic, the aggregate impact of all parallel instruments across Europe could significantly lower the CO_2 price and hurt the dynamic efficiency of the EU ETS through this impact. In this chapter, we determine how sensitive the performance of the EU ETS is to the introduction of parallel instruments. Specifically, we zoom in on the conditions that would force the EU ETS into redundancy, *i.e.* driving the carbon price down to €0.

Stochastic analysis shows that redundancy of the EU ETS is certain if the parallel instruments trigger more abatement than 45 $MtCO_2$/yr. If parallel instruments trigger more abatement than 20 $MtCO_2$/yr, redundancy of the EU ETS depends on the economic growth rate in Europe. The lower the economic growth rate the greater the likelihood of ETS redundancy. The actual threshold levels for EU ETS redundancy can be significantly below the reported thresholds if either policymakers or firms lack full commitment to the EU ETS. The commitment of policymakers may weaken if the CO_2 price is low, but not yet zero. This may lead them to pull the plug on the scheme, or at least suggest doing so, thereby affecting expectations to that end in the market. Similarly, firms may lose faith in the scheme and start dumping the emission allowances that they hold on stock. Such behavioural influences, that we have not modelled, may drive the price down to zero even if the impact of parallel instruments is below the 20 $MtCO_2$/yr threshold. If policymakers prioritize a strong impact of the EU ETS on investment behaviour of firms under the scheme, the results suggest that they should refrain from introducing parallel instruments if the carbon price is already weak.

In our analysis, we differentiate between two types of parallel instruments. Type 1 parallel instruments are aimed at ETS sectors and effectively reduce the carbon intensity of production in those sectors (*e.g.* a biomass co-firing mandate). Type 2 instruments are aimed at non-ETS sectors and lower the production levels in ETS sectors (*e.g.* instruments that promote households to install solar panels reduce the need for centralized electricity, the production of which falls under the EU ETS). The results show that Type 2 instruments lead to a stronger depreciation of the EU ETS carbon price than Type 1 instruments. This can be explained by the fact that Type 2 instruments lead to burden shifting between sectors: investments by non-ETS sectors effectively reduce the need for ETS sectors to invest in CO_2 abatement technologies.

The results can help policymakers to weigh more accurately the potential costs that are involved when considering the introducing of either of the two types in terms of reduced strength of the EU ETS incentive.

1.7. Chapter 4 – The EU ETS in the policy mix: measuring the impact of instruments in the German power sector on the performance of the EU ETS

In Chapter 3, we analysed to what extent the EU ETS performance depends on the impact of parallel instruments that are in force alongside. We found that the collective impact of parallel instruments could, theoretically, force the EU ETS carbon price permanently down to €0. In reality, the EU ETS carbon price has so far remained on average very low and far below prior expectations. Therefore, it seems a logical next step to try to better understand the impact of parallel instruments on the current performance of the EU ETS. This is true, the more so because their role has remained rather unclear so far.

To quantify this effect more precisely, in Chapter 4, we zoom in on a specific real-life case study. We examine how sensitive the EU ETS CO_2 price is to the introduction of two parallel instruments with substantial scope that have been in force in Germany alongside the EU ETS for several years, and still are. Specifically, we examine the interaction effects between the EU ETS and the German Feed-In Tariffs (FITs) and the German Nuclear Phase Out (NPO). Both instruments primarily work via the power sector.

We choose to focus on these instruments for three reasons. First, the German power sector is the largest national power sector within the EU ETS, covering about 15% of all emissions under the EU ETS. Second, these instruments are expected to have a considerable effect on the CO_2 emission output of the German power sector. Finally, it is impossible to accurately model the underlying factors that determine the impact of all parallel instruments that are in force today across Europe. So, apart from the two parallel instruments that are modelled explicitly, the impact of other parallel instruments is covered in a stylized manner.

Rathmann (2007), Abrell and Weigt (2008) and Traber and Kemfert (2009, 2012), have performed similar case study analyses, but have done so with a static model and thus a more simple representation of the EU ETS. A first disadvantage of that more simple approach is that it disregards the effect that the banking provision has on the EU ETS impact. Via banking, firms can, for instance, offset a short position in one year with surpluses from previous years. This can have a pervasive impact on the EU ETS effectiveness. Models of the EU ETS should therefore account for the cumulative supply and demand of allowances over an extended period of time to more accurately assess the time profiles regarding the need for CO_2 abatement activity and the level of the carbon price. A second backdrop of the static models is that the effect of parallel instruments on the carbon price may be temporary, or at least be of a different magnitude over time. Such dynamics cannot be accurately captured in a static model.

We extend the dynamic stochastic simulation model of the EU ETS, which was developed in Chapter 2, with a module that provides a detailed representation of the German power sector and the FITs and NPO. Apart from the stochasticity that was already present in the original model, the following variables are now also stochastically sampled: German electricity demand growth, fuel price changes of five fuels, on- and off-shore wind power and solar irradiance levels. The stochastic approach ensures that we do not make implicit technological choices by fixing important input parameters to a certain level. The module accounts for 22 different electricity generation technologies. Based on this detailed model configuration, we are able to draw a more complete and accurate picture of the impact of the German FITs and NPO on the performance of the EU ETS.

We find that the combined impact of FITs and the NPO on the EU ETS leaves the overall emission level in Europe unchanged, yet depreciates the EU ETS carbon price with an average of €5 (-14%) in 2030. Given that all 30 countries under the EU ETS have implemented a much wider range of additional parallel instruments, the results suggest that parallel instruments in general are a prominent driver behind the relatively low carbon prices witnessed. In fact, with a rough estimation, we estimate that the carbon price is €20, or 50%, below the 2030 level that it would have reached in absence of parallel instruments across the EU. For a detailed methodological description we refer to the chapter itself. Complete redundancy of the EU ETS under the weight of parallel instruments seems unlikely, although such a scenario cannot be ruled out if the economic growth rates remain low while fuel prices favour low-carbon alternatives. We suggest that a reduction in the number of policy targets, alongside the target to reduce CO_2 emissions, is necessary to ensure that the EU ETS can structurally drive investment behaviour across Europe. Alternatively, the policy targets that interfere the strongest with the performance of the EU ETS, such as targets regarding the deployment level of renewables, could be set to a less ambitious level.

1.8. Chapter 5 – Epilogue

In the epilogue, we summarize and reflect on the main findings of this study. Also, we discuss recent proposals by European policymakers to amend the current design of the EU ETS. Finally, we provide recommendations for further research.

2. STOCHASTIC SIMULATION OF CO_2 EMISSIONS TRADING IN EUROPE: WILL THE EU ETS DRIVE INVESTMENTS IN CCS?

2.1. Introduction

Various studies suggest that Europe cannot achieve the 2050 greenhouse gas emission reduction targets without serious investment in Carbon Capture and Storage (CCS) (IPCC, 2005; EC, 2009b; IEA, 2010, 2011). Given the lead-times to bring CCS to technological maturity, it therefore seems important to initiate serious CCS investments in pilot- and demo-projects at relatively short notice. This requires an effective incentive system. Although, incentives are currently primarily focused on subsidies, it seems plausible that in further maturity stages subsidizing the wider application of CCS will become unsustainable as this would require too many public resources. Making CCS a mandatory technology also seems unlikely given the non-market nature of such a measure. Essentially CO_2 emission penalties therefore remain as a key incentive to trigger CCS investments.

The only system that has tried to introduce such a CO_2 penalty on a European scale so far is the EU emissions trading scheme (EU ETS), which allocates emission allowances to installations and enables trading of these so that a market-based allowance price results. However, this price is uncertain given its dependence on volatile allowance demand from carbon emitting installations, which also has an impact on the return and timing of investments in abatement technologies, such as CCS. Consequently, the magnitude of allowance demand volatility could make or break the effectiveness of the EU ETS as a serious trigger for CCS deployment. In this study, we assess the extent to which allowance demand volatility leads to carbon price uncertainty and how this affects the scope for and timing of investments in CCS under the EU ETS.

Several techno-economic studies have tried to assess the potential role of CCS as a carbon abatement option in the energy system (see *e.g.* Stangeland, 2007; Odenberger *et al*., 2008; Broek *et al*., 2010; Odenberger and Johnsson, 2010; Broek *et al*., 2011; IEA, 2011;

Strachan *et al.*, 2011). These studies, however, are deterministic, *i.e.* they do not explicitly take into account to what extent year-on-year allowance demand and carbon price volatility affects investment behaviour vis-à-vis CCS technology. In fact, the studies typically rely on assumed linearly rising or constant carbon prices. Secondly, linearly decreasing emission caps are used to infer the need for abatement over time, thereby solely focusing on allowance supply levels and ignoring the ability to bank allowances if they are in surplus. In reality, the need for abatement (*i.e.* the scarcity of allowances) is ultimately determined by the interaction between demand and supply of allowances and banking of surplus allowances from earlier periods. Most studies disregard these interactions. Both methodological aspects, deterministic modelling and neglected interaction between the drivers of allowance scarcity, have in common that they create an overly optimistic scenario with respect to the stability and predictability of the EU ETS incentive mechanism, and thus its ability to effectively drive investments in capital intensity technologies with a long lead-time.

Therefore, in this study, we present a novel simulation methodology to assess the effectiveness of the EU ETS to trigger CCS deployment. We employ a model that does include interaction between the key drivers of an emissions trading scheme, including stochastic allowance demand volatility and allowance banking behaviour given heterogeneous firm-level carbon price expectations and investment opportunities. By means of a Monte Carlo simulation, confidence intervals are obtained regarding the forecasted long-term carbon price development and the deployment levels of various types of CCS. The model aims at presenting the potential impact of the CO_2 penalty via the EU ETS on CCS investment in a more realistic perspective. Note that other factors that also may slow down CCS deployment, such as societal acceptance problems (Alphen *et al.*, 2007; Huijts *et al.*, 2007). Also, technological and infrastructural obstacles may slow down or halt deployment (Stigson *et al.*, 2012). None of these factors have been explicitly included in the analysis. This reinforces our point that much of the analysis in the literature is likely to be based on overly optimistic scenarios regarding CCS deployment.

2.2. Methodology

Modelling CCS investment is commonly based on exogenously introducing incentives in the models. In other words, EU ETS allowance prices are taken as given and then introduced into the investment equation while feedbacks to the EU ETS allowance price are disregarded. For example, in reality, the economic growth rates as well as investments in CO2 abatement technologies affect the demand for EU ETS allowances, and thereby the EU ETS allowance price. We have chosen to make such feedback loops endogenous in our model by introducing a new concept called the Fundamental Carbon Price Indicator (FCPI). This indicator represents the theoretical long-term equilibrium EU ETS allowance price as derived from the model. The FCPI does not include the impact of short-term allowance price disruptions based for example on speculation, but it is rather based on the interaction between the following four fundamental drivers of the carbon price: *allowance supply*, *allowance demand, allowance banking* and the *opportunity costs of abatement technologies* that firms under the EU ETS are facing.

The FCPI trajectory can be interpreted as a long-term carbon price forecast, because the actual market price for carbon allowances is expected to converge to the FCPI. To understand this, we consider a situation where the market price for allowances is considerably higher than the FCPI (*e.g.* due to speculation). This would trigger extra abatement activity and a reduction of demand beyond the equilibrium point, leading to a surplus of allowances. The surplus would put downward pressure on the carbon price and lead to convergence of the market price towards the FCPI.

In this model, a merit order of abatement options is assumed whereby the lowest-cost options are applied first. With a cumulatively increasing level of allowance scarcity over time, a growing number of abatement technologies will be applied.[5] The crucial questions in this study are thus:

- when are various types of CCS expected to become part of the mix of abatement options,
- what is the required scale of deployment of these types of CCS in order to comply with EU ETS regulation and, most importantly,
- how uncertain are these forecasts?

The uncertainty of the forecasts is of particular importance because investors will be unlikely to invest in a technology if its long-term viability is highly uncertain. This is especially true for CCS, as it involves high capital requirements, long lead times and complex infrastructural planning.

2.2.1. *The fundamental drivers of the FCPI*

The first fundamental driver of the FCPI is carbon *allowance supply*, for which allowance allocation policy is crucial. An allowance represents the right to emit one tonne of CO_2 into the atmosphere and the total number of allowances that is issued to firms per year is capped. Furthermore, European legislation requires that the cap is annually reduced over time in a linear fashion (EC, 2009a), thereby forcing the overall emission level downwards.

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[5] Disinvestments (*e.g.* following a drop in the allowance price) are not included in the analysis.

However, a lower cap does not necessarily mean that firms are forced to immediately invest in abatement technologies as suggested in various papers that apply constant economic growth rates (see *e.g.,* Odenberger and Johnsson, 2010). Recessions could lead to a reduction of the demand for allowances that is larger than the reduction of the cap, allowing firms across Europe to build-up reserves of banked allowances for later use.

Therefore, it is also important to explicitly incorporate *allowance demand* as the second fundamental driver of the FCPI into the model. Not only does this make the investment decision-making process much more explicit, but it also enables a relatively simple introduction of stochastics in the model.

Allowance banking is the third driver of the FCPI. If allowances are scarce in any year, previously banked allowances can provide an additional source of allowance supply, thereby reducing the immediate need for carbon abatement. In our model, we introduce a new approach to allowance banking behaviour based on the assumption that companies across Europe have heterogeneous carbon price expectations (because they operate under imperfect information) and investment opportunities.

The opportunity cost of abatement faced by firms under the scheme is the fourth driver of the FCPI. The opportunity costs are expressed as marginal abatement cost of the next available technology, whereby technologies are ranked according to a merit-order whereby the lowest-cost abatement opportunities applied first followed by more expensive technologies, until demand and supply return to equilibrium. The marginal cost of the last technology that is applied equals the equilibrium FCPI.

By simulating this investment process on a year-to-year basis, and applying stochastic modelling to account for allowance demand uncertainty, confidence intervals of the FCPI and CCS deployment rates are calculated based on 2,000 Monte Carlo model runs.

Obviously, more factors driving CCS investment behaviour can be distinguished than covered in this model. Some of these drivers are in fact very hard to model at all because of their qualitative nature, although they can still be important in actual decision making. Examples are societal acceptance of elements of the CCS value-chain (notably storage), unexpected variation in technological learning rates, transaction costs due to organizational and administrative hurdles. All these factors have not explicitly been taken into account in the modelling, but all, except for positive learning rate surprises, tend to slow down CCS deployment.

The *allowance supply regime* assumed in this research reflects current ETS legislation and is therefore exogenous. The simulation starts in 2008, as firms were allowed to bank surplus ETS allowances for the first time in this year while 2030 is the horizon year for our simulation. The components of the *allowance supply* and the associated input values over time are presented in Section 2.2.2. *Allowance demand* and all of its components follow in Section 2.2.3. Subsequently, the algorithm that is applied to model *allowance banking* is presented in Section 2.2.4. Key input assumptions of the merit-order abatement cost curve and the algorithm of the technology selection process are laid out in Section 2.2.5.

2.2.2. Allowance supply

The unit of analysis for *allowance supply* is the total number of issued allowances (in $MtCO_2$ equivalent) in year t by the regulator of the EU ETS. Allowances are supplied to the market through various mechanisms. The total supply of allowances in Phase II and III can be expressed by:

$$AS_t = (C_{t-1} - AR_t)\varepsilon + INER_t + LD_t + 300_t \qquad for\ t = [2008, \ldots, 2030] \qquad (2.1)$$

The values for AS_t are shown in the last row of Table 2.1. Below follows a detailed outline of the various sources of allowance supply, based on European legislation.

C_{t-1} is the official EU ETS cap of all 30 countries[6] combined at $t-1$. AR_t represents the annual reduction of the cap in year t. The first term is multiplied by ε, which is equal to 0.95 during Phase II (2008-2012) and III (2013-2020) of the EU ETS, and equal to 1 for the period after 2020. We hereby take into account that 5% of the overall cap during Phase II and III is reserved in the New Entrants Reserve (NER) for new installations that enter the EU ETS. $INER_t$ represents the flow of allowances from the New Entrants Reserve to new entrants in year t. LD_t represents the flow of allowances obtained via the Linking Directive in year t and 300_t represents the flow of allowances auctioned via the NER300 program in year t. Each of these parameters will now be explained in more detail. The values of all input parameters over time are shown in Table 2.1.

During Phase II the annual cap (C_t) is equivalent to 2,083 MtCO$_2$. Starting in Phase III (2013-2020) the cap will be linearly reduced over time. AR_t represents this annual reduction of the cap (see row three in Table 2.1). The EU ETS directive states that the annual reduction is linear, calculated from the mid-point of Phase II (2008-2012), and equal to 1.74% of the average allowance cap between 2008 and 2012 (EC, 2009a). Because the reduction of the cap has started in 2013, but is calculated from the mid-point of Phase II (end of 2010), AR_t is three times higher in 2013 (compared to later years) to make up for the fact that the cap remained constant throughout the last two years of Phase II.

Stocks of and flows out of the NER are shown in row four (NER_{stock}) and five ($INER_t$) of Table 2.1 respectively. Note that stock figures in the table represent the level of stock by the end of each respective year. ETS legislation states that any remainders in the

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[6] The 27 EU member states plus Iceland, Liechtenstein and Norway. Croatia entered the EU in July 2013, and started participating in the EU ETS from the 1st of January of 2014 but was not considered in this analysis.

reserve by the end of Phase II can be auctioned or cancelled by the respective national governments holding the remainder. Assuming that national governments maximize their own welfare, we assume that any remaining allowances in the reserve are auctioned by each respective government controlling the left-over. That implies a total flow ($INER_t$) equivalent to 420 $MtCO_2$ out of the reserve during 2012 and a depleted stock (NER_{stock}) by the end of 2012. The total flow in 2012 consists of 60 $MtCO_2$ of allowances that we estimate to be issued to new installations and 360 $MtCO_2$ worth of allowances that are left over in the reserve to be auctioned during 2012.

Table 2.1: Input parameters for allowance demand in $MtCO_2$ during Phase II and III[a]

	Phase II					Phase III								Phase IV								Phase V	
t	'08	'09	'10	'11	'12	'13	'14	'15	'16	'17	'18	'19	'20	'21	'22	'23	'24	'25	'26	'27	'28	'29	'30
C_t	2,083	2,083	2,083	2,083	2,083	1,974	1,938	1,902	1,866	1,829	1,793	1,757	1,721	1,684	1,648	1,612	1,576	1,539	1,503	1,467	1,431	1,394	1,358
AR_t	0	0	0	0	0	109	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36
NER_{stock}	521	501	461	420	0	384	329	274	219	165	110	55	0	0	0	0	0	0	0	0	0	0	0
$INER_t$	0	20	40	40	420	55	55	55	55	55	55	55	55	0	0	0	0	0	0	0	0	0	0
300_{stock}	300	300	300	280	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300_t	0	0	0	20	240	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LD_t	82	82	137	254	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114
AS_t	2,061	2,081	2,156	2,294	2,754	2,085	2,010	1,976	1,941	1,907	1,873	1,838	1,804	1,799	1,762	1,726	1,690	1,654	1,617	1,581	1,545	1,509	1,472

[a] *The Phase III NER is 5% (739 $MtCO_2$) of the cap; all numbers are rounded and may not add up*

The size of the Phase III NER is equal to 739 $MtCO_2$ (5% of the Phase III cap). However, European policy makers have set aside 300 $MtCO_2$ worth of allowances from this Phase III NER in a separate 'NER300 program' that starts already in 2008. Allowances in the NER300 program were set aside to be auctioned to firms already covered by the scheme, instead of being allocated to new entrants. The auction revenues are earmarked to support CCS demonstration projects and development of renewable energy technologies (EC, 2009a). Allowances reserved in the NER300 program were auctioned between 2011 and early 2013 until complete depletion of the stock.[7] This is shown in row six (300_{stock}) and seven (300_t) in Table 2.1 for the stock of and flow out of the NER300, respectively.

Controlling for the NER300, 439 $MtCO_2$ worth of allowances are still left in the Phase III NER at the start of 2013. This remainder is expected to be issued evenly (55 $MtCO_2$ per annum) over the remaining years of Phase III. So at the end of 2013, the NEW stock equals 439 - 55 = 384 $MtCO_2$ (see NER_{stock} in Table 2.1).

The final source of allowances that is present in Equation 2.1 is the Linking Directive (LD_t), which stipulates that installations are allowed to obtain CDM (Clean Development Mechanism) allowances on top of the official EU ETS cap. LD_t represents the flow of allowances obtained via the Linking Directive in year t. The amount of allowances obtained through this mechanism is limited to a theoretical maximum of 13.3% of the EU ETS cap in year t during Phase II and to a total of 1,584 $MtCO_2$ between 2008 and 2020 (Graus *et al.*, 2009). In 2008, 2009, 2010 and 2011, the realized number of obtained allowances was 82, 82, 137 and 254 $MtCO_2$ respectively. The remaining potential (an additional 1,029 $MtCO_2$ can be obtained until the maximum of 13.3% is reached) is assumed to be used evenly over the remainder of Phase II and Phase III. Furthermore, the Linking Directive is assumed to be continued at the same rate after 2020 in the Base Case scenario. The effect of a possible discontinuation after 2020 is tested in Section 2.3.3.

2.2.3. Allowance demand

Total demand for allowances at the beginning of year t, can be written as:

$$AD_t = (AD_{t-1} - TA_{t-1} - RD_{t-1})(1 + EG_t) + RD_t + NE_t \qquad for\ t = [2008, \dots, 2030] \tag{2.2}$$

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[7] The monetization of allowances from the NER300 program is undertaken by the European Investment Bank. A timeline of the monetization process is available on the project website: www.ner300.com.

The total demand for allowances in year t is determined by the total allowance demand at the beginning of the previous year (AD_{t-1}), reduced by the total level of abatement (TA_{t-1}) and residual demand (RD_{t-1}) in the previous year. Residual demand can be positive if firms fail to surrender sufficient allowances to cover their emissions, otherwise RD_t is equal to 0. Following the EU ETS directive (EC, 2009a), firms incur a non-compliance penalty of 100 euros per tonne of CO_2 if they fail to surrender sufficient allowances. On top of that penalty, non-compliant firms are obliged to buy (and surrender) extra allowances in the next year in order to cover these emissions. In our model, the extra demand for allowances is called 'residual demand', RD_t is an endogenous model parameter that can be positive if the need for abatement potential and/or banked allowances is greater than the potential/stock available in any year of the simulation.

RD_{t-1} is subtracted from the total demand in the previous year (AD_{t-1}) in Equation 2.2 because it is not structural; it is a consequence of compliance failure in year $t-2$. The structural demand from the previous year is multiplied by a growth factor ($1+EG_t$), where the latter term (EG_t) is a stochastically sampled percentage growth of emissions in year t. Finally, the total demand for allowance is determined by adding residual demand at t (RD_t) and the demand of new entrants to the EU ETS (NE_t).

In 2008, 2009, 2010, 2011 and 2012, the aggregate allowance demand under the EU ETS (AD_t) was equal to 2,118, 1,873, 1,934, 1,898 and 1,786 $MtCO_2$, respectively. These values are used as exogenous inputs. For subsequent years, the level of emissions is simulated based on Equation 2.2.

The parameter EG_t captures the stochastically simulated market level volatility of allowance demand. The parameter is sampled in each year of the simulation from a normal distribution with a mean of 0.33% and a standard deviation of 2.08%. The mean of the distribution is based on the projected average growth of emissions in EU ETS sectors until 2030. We assume a mean emissions growth of 0.33% based on World Energy Outlook estimates (IEA, 2009) and the GHG abatement studies by McKinsey (Enkvist and Naucler, 2009; Enkvist *et al.*, 2010).[8] The standard deviation is based on the historical standard deviation of industry level emissions, which was 2.08% for European industrial sectors between 1990 and 2008 (EEA, 2011b).

In 2009, emissions under the EU ETS decreased by more than 10% (EEA, 2011b) following the worldwide financial crisis that started in late 2008. This steep drop in emissions contrasts sharply with otherwise fairly stable emissions levels. Due to the severity and uniqueness of the economic crisis that followed, this observation was excluded when calculating the historical standard deviation in industrial carbon emissions. However, the impact of another crisis year with a similar magnitude is tested as a separate scenario in Section 2.3.3.

NE_t is equal to the added CO_2 emissions from new entrants to the EU ETS, which primarily replace old installations that are decommissioned (Lewis, 2008). As a result, NE_t is not equal to the number of issued allowances from the NER (indicated by $INER_t$, see Table 2.1 for the input values). Instead we assume that[9]

$$NE_t = {}^{1}\!/_{3}\, INER_t \qquad for\ t = [2008, \ldots, 2030] \qquad (2.3)$$

Finally, TA_{t-1} represents the total abatement efforts in the previous year through the deployment of abatement technologies in $MtCO_2$. Obviously, we account for these abatement

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[8] This is a scenario where abatement levers are assumed to be implemented at the historical pace thereby controlling for a ramp-up in abatement efforts following the introduction of the EU ETS.

[9] This holds with an exception for 2012, where $NEt = (INER_t - 360)$. 360 $MtCO_2$ represents the leftover in the Phase II NER and is auctioned without any new installations entering the scheme.

efforts to calculate the demand for allowances in year t. TA_{t-1} is an endogenous model parameter and will be further specified in Section 2.2.5.

2.2.4. *Allowance banking*

Allowance demand is subtracted from *allowance supply* to arrive at the gross allowance surplus in year t:

$$GAS_t = AS_t - AD_t \qquad for\ t = [2008, \dots, 2030] \tag{2.4}$$

Positive values imply a surplus, while negative values imply a shortage of allowances in year t. A surplus is added to the existing reserve of banked allowances (BA_t) while a shortage would lead to usage of banked allowances and a reduction of the reserve. That is:

$$If \quad GAS_t \geq 0 \quad then \quad BA_{t+1} = BA_t + GAS_t \qquad for\ t = [2008, \dots, 2030] \tag{2.5.1}$$

$$If \quad GAS_t < 0 \quad then \quad BA_{t+1} = BA_t - UBA_t \qquad for\ t = [2008, \dots, 2030] \tag{2.5.2}$$

If the market is in surplus, the change in the stock of banked allowances is equal to the gross allowance surplus (GAS_t). Alternatively, in case of allowance scarcity, the stock is reduced by the number of used banked allowances at t (UBA_t). How we determine UBA_t will be explained below. At the start of the simulation in 2008, there are no allowances in the reserve ($BA_{t=2008} = 0$). Of course, the amount of used banked allowances is no larger than the (negative) gross allowance surplus, hence $UBA_t \leq |GAS_t|$.

By controlling for the usage of banked allowances, we arrive at the net allowance surplus (NAS_t) that determines the abatement in year t:

$$If \quad GAS_t < 0 \quad then \quad NAS_t = GAS_t + UBA_t \quad for\ t = [2008, \dots, 2030] \tag{2.6.1}$$

$$If \quad GAS_t \geq 0 \quad then \quad NAS_t = 0 \quad for\ t = [2008, \dots, 2030] \tag{2.6.2}$$

If the market for allowances is in surplus ($GAS_t > 0$), the level of abatement is 0, otherwise Equation 2.6.1 holds.

In case of allowance scarcity, the gross allowance scarcity is equal to the sum of carbon abatement activity and the use of banked allowances in that year ($|GAS_t| = |NAS_t| + UBA_t$). Carbon abatement and the use of banked allowances are substitutes regarding EU ETS compliance. Firms can comply with EU ETS regulation either by investing in CO_2 abatement technologies, or by using banked allowances to cover their emissions. We determine the equilibrium between these two substitutes based on their relative cost. In the process, we find the equilibrium allowance price ($FCPI_t$). Below, we will explain this procedure in a detailed manner.

An example of an equilibrium between CO_2 abatement efforts and the use of banked allowances is shown in Figure 2.1 (for a randomly simulated year t). The x-axis shows that the gross allowance scarcity ($|GAS_t|$) in this example is 88 $MtCO_2$. In equilibrium, the sum of abatement efforts ($|NAS_t|$) and the use of banked allowances (UBA_t) covers the entire gross allowance surplus. The CO_2 price is shown on the *y*-axis.

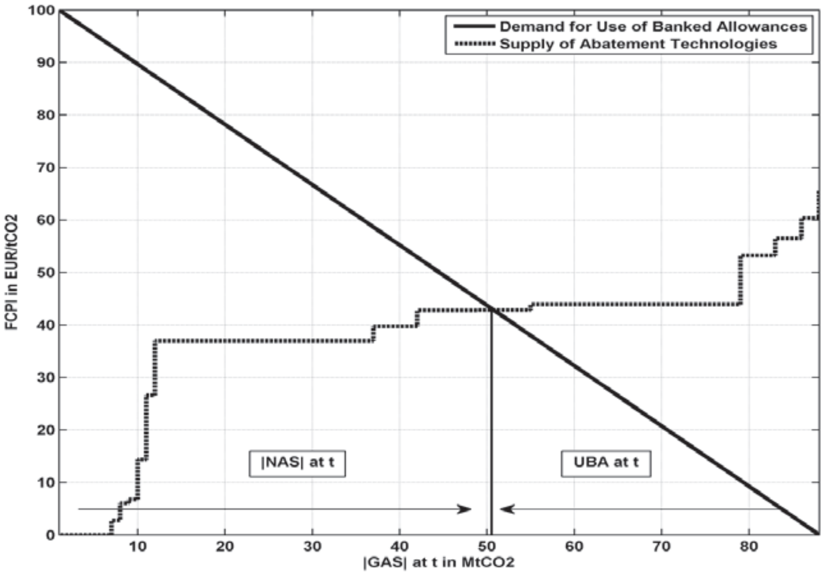
The two curves (*Demand for the Use of Banked Allowances* and *Supply of Abatement Technologies*) depict the use of banked allowances and the relative cost of CO_2 abatement respectively. Note that, if the CO_2 price equals zero, both the amount of abatement ($|NAS_t|$) and the use of banked allowances (UBA_t) equal zero (UBA_t should be read from right to left on the x-axis, as indicated by the arrow). As the CO_2 price increases, more abatement technologies become economically viable, and hence abatement efforts increase. Also, as the

CO_2 price increases, more firms are willing to use their banked allowances. Demand for the use of banked allowances refers to the desire of the owner of the banked allowance to use it in order to comply with ETS regulation. Using a banked allowance becomes more interesting with a rising CO_2 price because the alternative to using a banked allowance is buying allowances on the exchange against the going CO_2 price. The equilibrium CO_2 price ($FCPI_t$) is found where both curves intersect. The shapes and assumptions behind the two curves will now be described in more detail.

The relative costs associated to CO_2 abatement are represented by the *Supply of Abatement Technologies* curve. This curve shows at which allowance price a specific technology becomes available to investors as an economically viable investment option. Logically, the higher the $FCPI$ (depicted on the y-axis), the more technologies become economically viable, and the more firms are willing to invest in CO_2 abatement. Note that, in the sampled year t that is depicted in Figure 2.1, the lowest-cost abatement opportunities have a near-zero CO_2 price level above which they become economically viable. This is because we have assigned a cost of €0.01 to abatement opportunities that, in the original data set, were estimated to be available at a negative cost. These negative-cost abatement opportunities represent technologies where the life-cycle savings outweigh the costs. Due to the usual lead-times in investment in new technologies by firms and their acting only on no-regret options that they consider to be sustainable, we have assumed that firms will not immediately capitalize on these no-regret abatement opportunities but only when faced with allowance scarcity. We assign a marginally low positive CO_2 price to reflect this assumption. Also, by eliminating negative cost levels in this manner, we ensure that the demand and supply curve will always intersect within the interval $[0, GAS_t]$ on the x-axis. Specifics on the abatement technologies data set are further described at the end of section 2.2.5.

The *Demand for Use of Banked Allowances* curve in Figure 2.1 depicts the relative cost of using banked allowances. In absence of empirical data to estimate the shape of the curve, we make some simplifying assumptions. First, the relationship between the CO_2 price and the use of banked allowances is assumed to be linear. Second, at a CO_2 price of zero, the use of banked allowances is also zero. Firms have an incentive to hold on to all of their banked allowances if the price is 0 euros per allowance because additional allowances can be bought via the exchange (if needed) against zero cost. By refraining from using banked allowances, a firm can fully benefit from potential upward movements in the CO_2 price as the value of the portfolio of banked allowances would increase in that case. Third, if the CO_2 price equals the non-compliance penalty of 100 euros per allowance in year t, emitters fully rely on banked allowances to comply with ETS regulation (note that the curve intercepts the y-axis at a $FCPI$ level of 100 euros).

Figure 2.1: Equilibrium between the demand for the use of banked allowances and the supply of abatement technologies



We assume that the non-compliance penalty is viewed by emitters as the price ceiling. We do so because the non-compliance penalty has purposefully been set well above the anticipated CO_2 market price to deter firms from non-compliance (*i.e.* to ensure that compliance with ETS regulation is always cheaper the penalty on non-compliance). Note that, in reality, the level of the non-compliance penalty may not necessarily act as hard price ceiling. This is because non-compliance also implies that firms have to buy additional allowances in the subsequent year to make up for the non-compliant behaviour (defined as residual demand in section 2.2.3). These additional costs, that depend on the future CO_2 price level, could be considered as an integral part of the non-compliance penalty. We disregard this potential driver of the price ceiling for three reasons. First, these additional costs accrue only to those emitters that have been non-compliant (and not to the entire market). Second, inclusion of a forecast of the CO_2 price would overly complicate the analysis. Third, if the market price approaches the current level of the non-compliance penalty, regulators are likely to respond by increasing the level of the non-compliance penalty. We assume that firms do not anticipate such regulatory adjustments.

At intermediate levels of the allowance price, in between zero and the price ceiling, the usage of banked allowances depends on firm-level allowance price expectations and investment opportunities.

We assume that across Europe firm-level price expectations and investment opportunities are heterogeneous. For example, some firms use (hold on to) their banked allowances at an intermediate level of the allowance price given their relatively low (high) price expectation or access to (lack of) alternative investment opportunities with a higher return. Logically, the number of firms that is willing to use banked allowances grows as the allowance price increases.

Formally, the *Demand for the Use of Banked Allowances* curve is defined as:

$$If \quad GAS_t < 0 \quad then \quad FCPI_t = NCP_t + \frac{NCP_t}{GAS_t}(|GAS_t| - UBA_t) \qquad for\ t = [2008, \ldots, 2030] \tag{2.7.1}$$

$$If \quad GAS_t \geq 0 \quad then \quad FCPI_t = 0 \qquad for\ t = [2008, \ldots, 2030] \tag{2.7.2}$$

NCP_t is the non-compliance penalty and (NCP_t/GAS_t) is the slope of the *Demand for the Use of Banked Allowances* curve. If the demand and supply for allowances result in a surplus in year t ($GAS_t \geq 0$), no banked allowances are used and neither is there a need for abatement. Consequently, the allowance price falls to zero ($FCPI_t = 0$).

$$UBA_t = \frac{|GAS_t|}{NCP_t} FCPI_t \tag{2.8}$$

From equations 2.7.1 and 2.7.2 we find that the use of banked allowances in year t (UBA_t) depends on the gross allowance shortage, the non-compliance penalty and the equilibrium CO_2 price in year t.[10] Note from Equation 2.7.2 that no banked allowances are used ($UBA_t = 0$) if that market for allowances is in surplus ($GAS_t \geq 0$).

In Figure 2.1, we find in equilibrium that the amount of abatement in year t equals 51 $MtCO_2$, the use of banked allowances equals 37 $MtCO_2$ and the FCPI equals €43. While Figure 2.1 depicted a scenario with plentiful abatement opportunities and plentiful banked allowances, Figure 2.2 presents a scenario with limited technical abatement potential. The technical abatement potential that is available (38 $MtCO_2$) is less than the gross scarcity of

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[10] Our linear approach in this study regarding the use of banked allowances is based on relatively simply assumptions regarding the banking strategies that firms apply. Among others, we have not explicitly considered the possibility of non-linearity (e.g. a convex, concave or s-shaped curve (Allen, 1938)), dynamically changing carbon price expectations, the historical build-up of banked allowances and who holds the stock (*e.g.* emitters that hold reserves for compliance purposes versus investors that hold the allowances for speculative reasons (Neuhoff *et al.*, 2012)). Further research in this regard could help to further improve the explanatory value of simulation results. Such an analysis, however, is outside the scope of this study.

Figure 2.2: Non-compliance, equilibrium with limited abatement potential

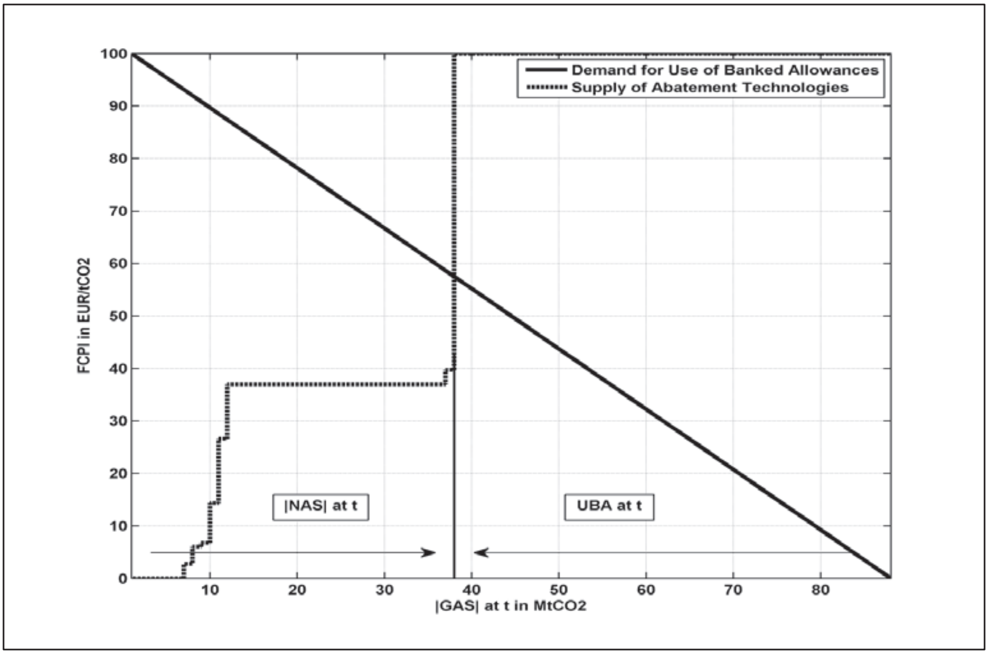
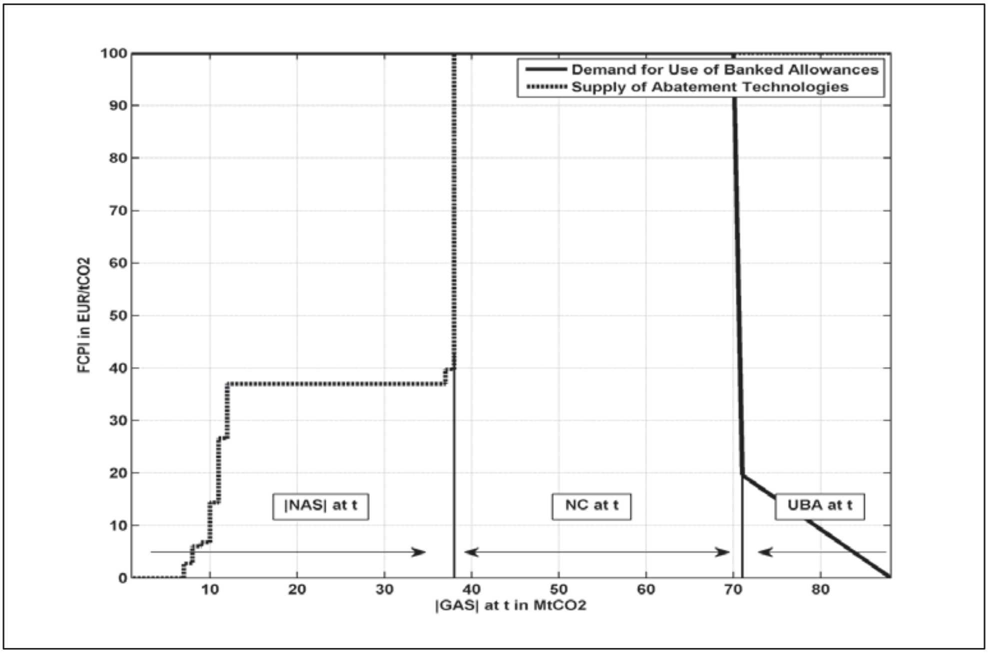


Figure 2.3: Non-compliance, equilibrium with limited abatement potential and banked allowances



allowances (88 $MtCO_2$). Therefore, a minimum of 50 $MtCO_2$ of banked allowances is needed to bring the market back into equilibrium. In order to reach that equilibrium, bidding for allowances continues until the carbon price reaches €58. At that level, a sufficient number of firms with banked allowances are willing to sell these (51 $MtCO_2$) for the market to clear.

Another special case is depicted in Figure 2.3, with the market having both limited abatement potential and limited banked allowances. Compared to Figure 2.2, the gross scarcity of allowances and the amount of abatement remain unchanged at 88 $MtCO_2$ and 37 $MtCO_2$, respectively. However, the use of banked allowances by firms is just 17 $MtCO_2$, thereby depleting the stock. With no other options left[11], firms are forced to pay the non-compliance penalty of €100 for each tonne of CO_2 emissions that is not covered by a surrendered carbon allowance. In case of non-compliance, the carbon price rises to the level of the penalty.

Taking the possibility of non-compliance into account, we add a term to Equation 2.6.1:

$$If\ GAS_t \leq 0 \qquad then \quad NAS_t = GAS_t + UBA_t + NC_t \qquad for\ t = [2008, \ldots, 2030] \qquad (2.6.3)$$

As mentioned in Section 2.2.3, apart from paying a penalty, European legislation states that firms are obliged to buy (and surrender) extra allowances in year $t + 1$ to make up for any non-compliance in year t.

Therefore,

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[11] Lowering of the production volume and/or carbon leakage is not considered in this study.

$$RD_{t+1} = NC_t \qquad for\ t = [2008, \ldots, 2030] \tag{2.9}$$

Legislators are likely to raise the non-compliance penalty once the carbon price approaches the current level of the penalty to discourage non-compliance. Therefore, we assume that the non-compliance penalty for the subsequent year is automatically increased by €5 each time the difference between the FCPI and the NCP is less than €10:

$$If\quad NCP_{t-1} - FCPI_{t-1} < 10 \quad then \quad NCP_t = NCP_{t-1} + 5 \quad for\ t = [2008, \ldots, 2030] \tag{2.10.1}$$

$$If\quad NCP_{t-1} - FCPI_{t-1} \geq 10 \quad then \quad NCP_t = NCP_{t-1} \qquad for\ t = [2008, \ldots, 2030] \tag{2.10.2}$$

2.2.5. *Deployment of abatement technologies*

Given a need for abatement at t ($NAS_t < 0$), the lowest-cost abatement opportunities are applied first, and others follow in merit-order, to minimize the overall costs of deployment. This linear optimization problem thus resembles a 'knapsack problem,' where each technology has an equal weight (1 tCO_2) but a varying value (marginal cost per tonne abated). The mathematical specification then becomes:

$$min \textstyle\sum_{k=1}^{78} MAC_t^k DC_t^k \quad subject\ to \quad \sum_{k=1}^{78} DC_t^k = |NAS_t| \quad where \quad DC_t^k \in \{0,1, \ldots, TAC_t^k\}$$
$$for\ t = [2008, \ldots, 2030] \tag{2.11}$$

Here, MAC_t^k is the marginal abatement cost and DC_t^k is the deployed capacity of technology k at t. A total of 78 abatement technologies are included. The deployable capacity of each technology is limited by TAC_t^k, the total abatement capacity of technology k at t. The scope for a specific technology k in year t will be evaluated based on:

$$TDC_t^k = \textstyle\sum_{s=2008}^{t} DC_s^k \qquad for\ k = [1, \ldots, 78],\ t = [2008, \ldots, 2030] \tag{2.12}$$

Here, TDC_t^k is the cumulatively deployed capacity of technology k since the start of the simulation. Total abatement across all technologies in year t alone (TA_t, see also Equation 2.2) is equal to the cumulatively deployed capacity of all individual technologies at t:

$$TA_t = \sum_{k=1}^{78} DC_t^k \qquad for\ \ t = [2008, \ldots, 2030] \tag{2.13}$$

Data on the abatement capacities and marginal costs of technologies across EU ETS sectors in the 27 EU-members were taken from the global GHG abatement studies by McKinsey (Enkvist and Naucler, 2009; Enkvist *et al.,* 2010). This dataset was used because of its geographical and multi-sector scope which matches the coverage of the EU ETS. The data is based on the original study in 2009 and was updated in 2010 to reflect higher fossil fuel prices and post-crisis expectations with respect to economic growth and the associated 'business-as-usual' emission levels. Marginal costs have been calculated assuming an upward trending oil price reaching 110 dollars per barrel in 2030 and an 8% interest rate to reflect private sector financing rates. The marginal costs have been converted to 2010 prices. All of the identified abatement potential from the power, cement, chemicals, petroleum & gas and iron & steel sectors is included in the study.

As far as the data is concerned, background information on the applied methods (Enkvist and Naucler, 2009) and recent updates and worldwide cost and capacity estimates (Enkvist *et al.,* 2010) can be found in the original reports.

2.3. Results

The Base Case simulation results are presented in Section 2.3.1. The sensitivity of the results to key assumptions and currently proposed adjustments to ETS regulation is tested in

Table 2.2: Simulation statistics (rounded) – Base Case

Output Parameter / t	2010	2015	2020	2025	2030
Mean Overall Abatement ($MtCO_2$/yr)	58	59	219	384	601
Mean Fundamental Carbon Price Indicator (€)*	0	1	31	45	38
Mean Total Emissions under the EU ETS ($MtCO_2$) *	1,934	1,870	1,882	1,737	1,552
Banked Allowances ($MtCO_2$) *	431	2,326	2,347	2,184	1,976

* See Figures 2.4, 2.6 and 2.7 for the confidence intervals

Section 2.3.3. Special attention is assigned to the effect of macro-economic allowance demand shocks (double-dip) on the results.

2.3.1. The Base Case

The confidence interval of the FCPI is given in Figure 2.4. Key statistics regarding the ETS are summarized in Table 2.2. Next to the FCPI, these statistics include the cumulative amount of abatement incentivized under the EU ETS, the emission level under the scheme ($AD_t - RD_t$) and the stock of banked allowances (BA_t).

In the first year of the simulation (2008), the market experienced a shortage of allowances which is reflected by a carbon allowance price of €31 (see Figure 2.4). The development of the FCPI resembles the pattern of the actual allowance market price development which peaked around €31 in 2008. By the end of 2008, the allowance price had dropped steeply as a result of the worldwide financial crisis. Carbon emissions dropped by more than 10% in 2009 (EC, 2010) which led to a build-up of allowances in later years (see Figures 2.5 and 2.6).

On average, until 2016, a surplus of allowances (GAS_t) is expected, after which the market is forecasted to experience allowance shortages until 2030. The confidence interval is shown in Figure 2.5.

Figure 2.4: Fundamental EUA price – Base Case

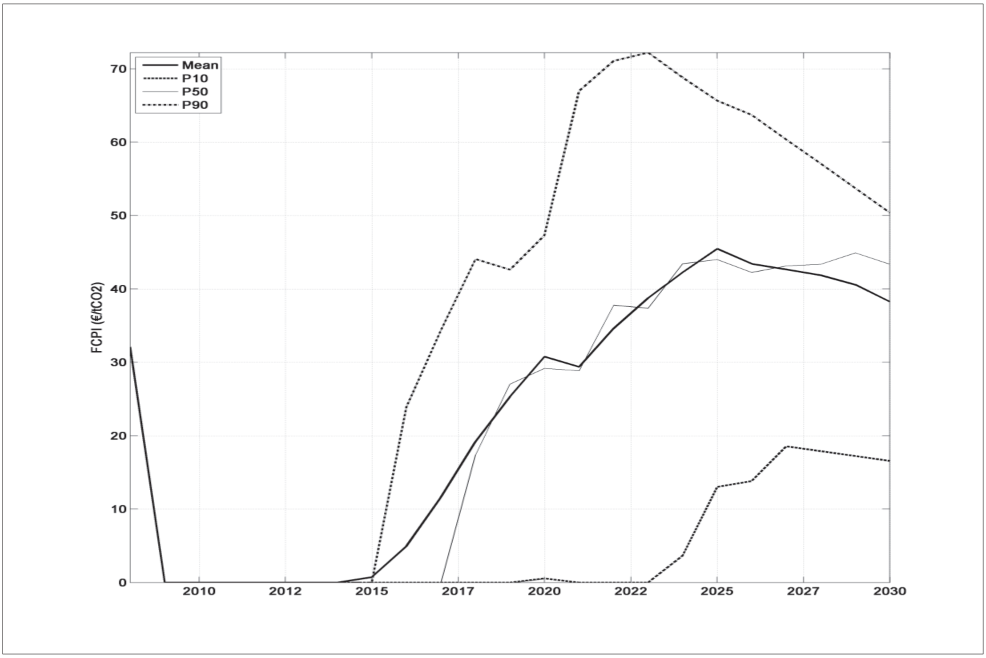


Figure 2.5: Annual gross allowance balance (in $MtCO_2$) – Base Case

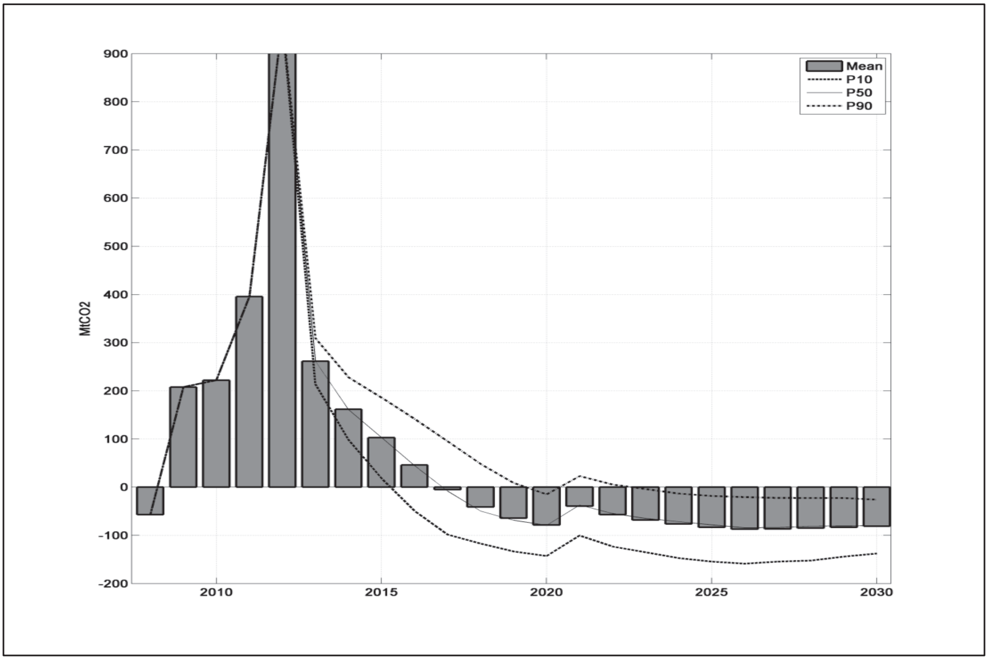


Figure 2.6: Stock of banked allowances – Base Case

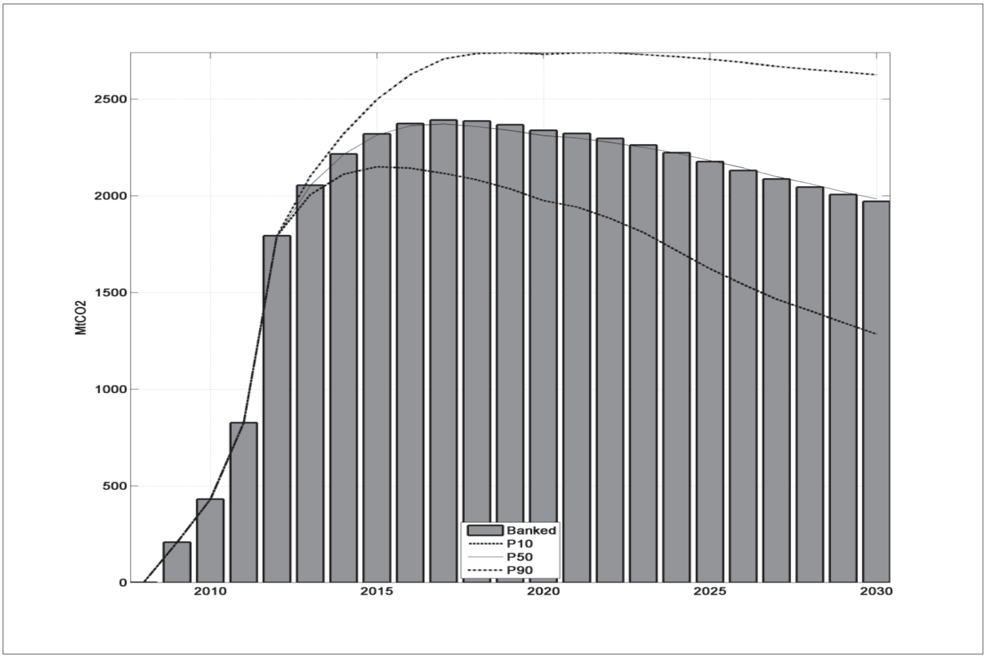
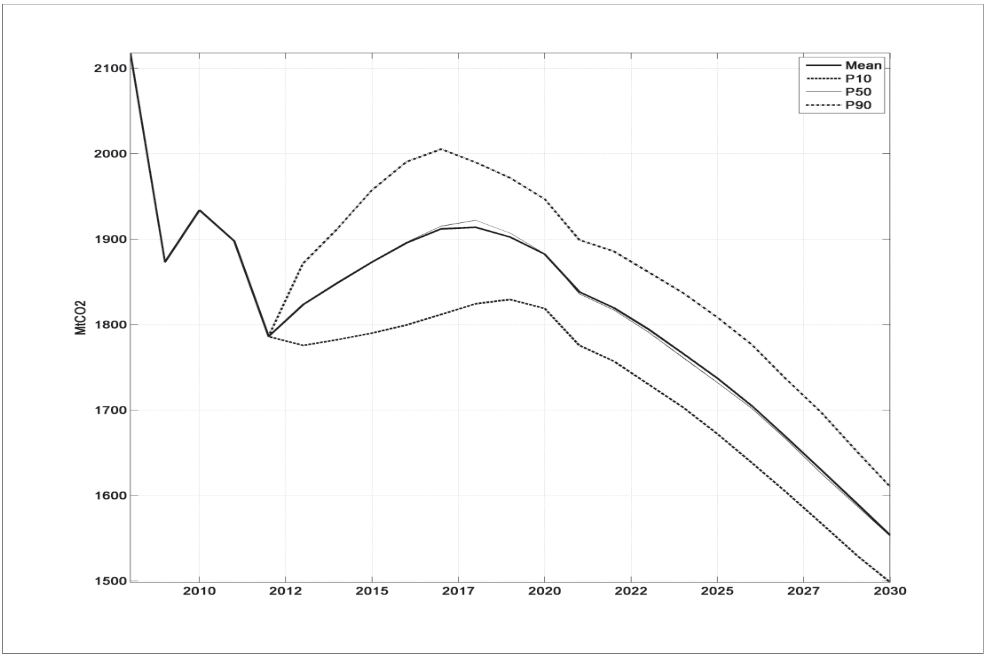


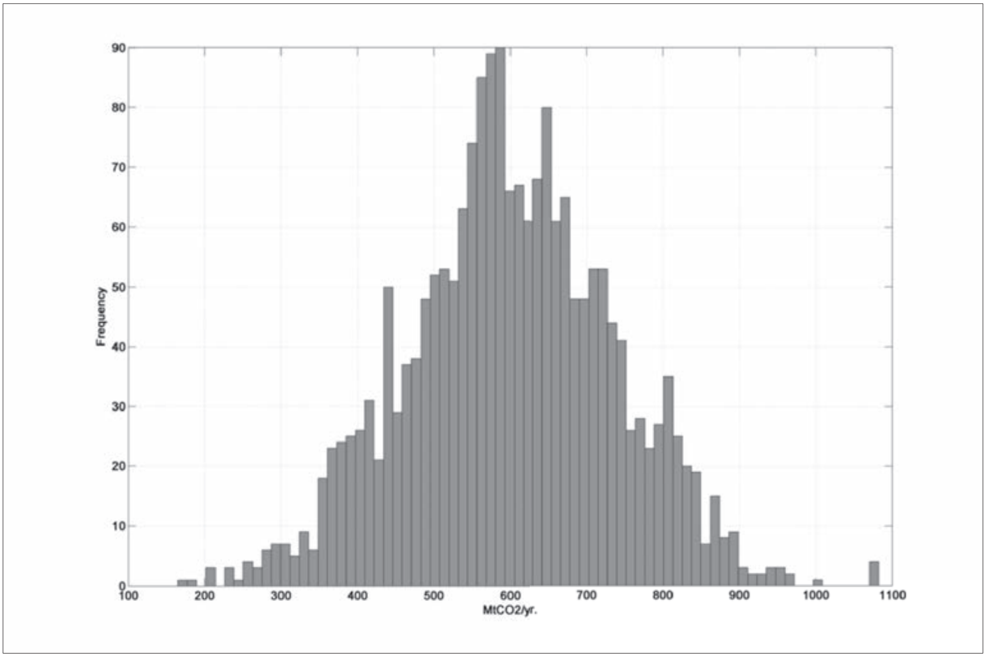
Figure 2.7: Emission level under the EU ETS (in MtCO$_2$/yr) – Base Case



The allowance surplus trajectory is reflected by the FCPI which is €0 in 2010, increases to €1 five years later and steeply climbs in subsequent years. As visualized in Figure 2.4, the price is forecasted to peak at an average of €45 in 2025 and subsequently to fall back to €38 in 2030.

The downward trend between 2025 and 2030 is the result of a larger availability of abatement potential combined with declining marginal abatement costs due to technological learning and a rising oil price. On average, 601 $MtCO_2$ of abatement is expected to be triggered by the EU ETS by 2030. However, as Figure 2.8 shows, there is considerable uncertainty around this number because the emissions growth rate (EG_t) is uncertain (in part driven by uncertain economic growth prospects). The standard deviation is 141 $MtCO_2$ and the lower and upper bound of the 80% confidence interval are 424 and 784 $MtCO_2$ respectively. In general, firms under the scheme thus face considerable investment uncertainty towards 2030.

Figure 2.8: Forecasted total abatement triggered by EU ETS until 2030 – Base Case



2.3.2. *CCS deployment*

Given the range of types of CCS and sectors in which it can be deployed, the scope for CCS in the Base Case is analysed at three different aggregation levels. Firstly, we look at the total deployment of CCS across all technology types k of all sectors combined in year t. Secondly, we analyse the totals per sector. Finally, we analyse the deployment level of each individual CCS technology type k.

2.3.2.1. TOTAL DEPLOYMENT OF CCS

Whereas the FCPI shows a downward trend from 2025 onwards, the total average scope for CCS progressively grows over time (see Figure 2.9). On average, 83 $MtCO_2$/yr of CCS abatement capacity is expected to be required across all sectors under the EU ETS by 2030. The ‘total CCS requirement’ frequency distribution for 2030, displayed in Figure 2.10, is skewed to the right (skewness = 0.91) and has “thick” tails (kurtosis = 3.19). The median is 58 $MtCO_2$/yr which is lower than the average, indicating that the deployment rate is likely to be significantly below the average.

2.3.2.2. SECTORAL DEPLOYMENT OF CCS

As far as the CCS deployment at a sectoral level is concerned, Table 2.3 shows that on average 67 $MtCO_2$/yr of CCS-based abatement is forecasted to be deployed in 2030 in the power sector, 14 $MtCO_2$/yr in the iron & steel sector, and 2 $MtCO_2$/yr in the chemicals sector, while in the petroleum & gas and the cement sectors no abatement potential is found. The associated confidence intervals are positively skewed, *i.e.* most of the observations lie below reported means for 2030. In fact, regarding the cement, petroleum & gas and chemicals sectors, Table 2.4 shows a 90% probability that the CCS deployment levels in these sectors will have values below 0 $MtCO_2$/yr, 0 $MtCO_2$/yr and 3 $MtCO_2$/yr respectively.

Figure 2.9: Total deployment of CCS in 2030 (in MtCO$_2$/yr) – Base Case

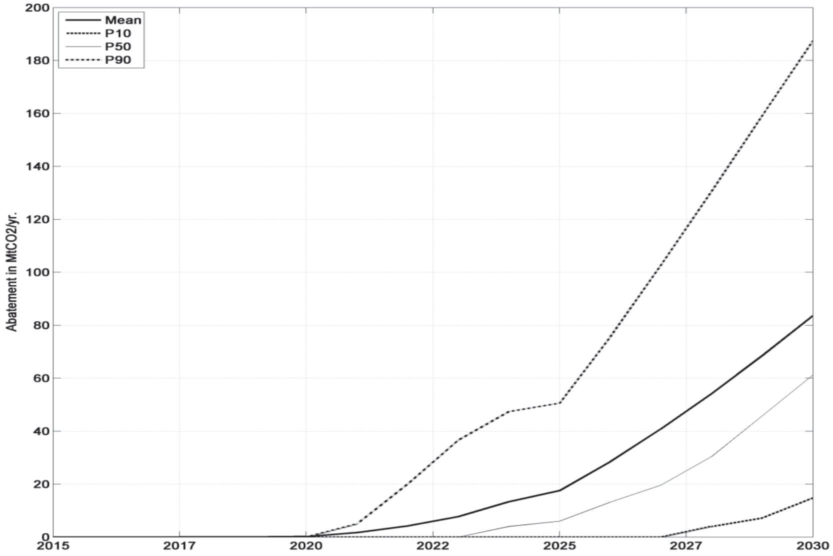


Figure 2.10: Total cumulative deployment of CCS (in MtCO$_2$/yr) – Base Case

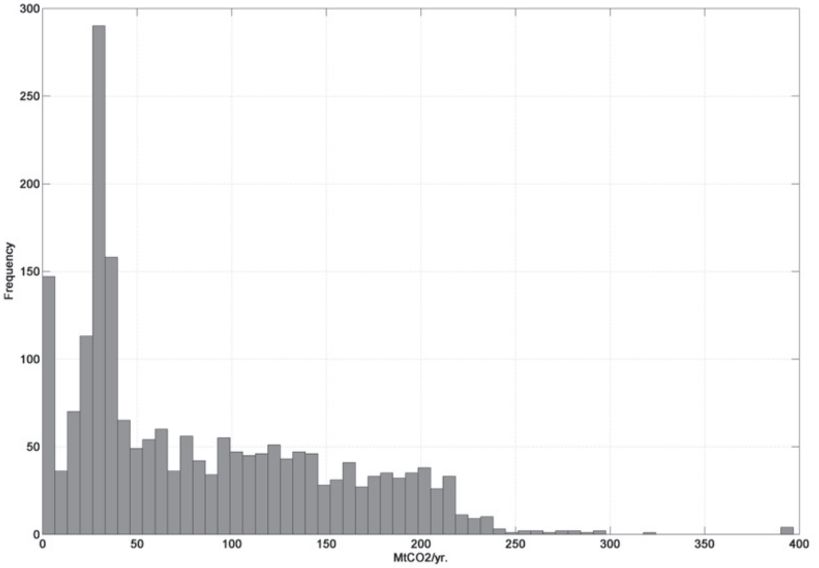


Table 2.3: CCS deployment at a sectoral level in $MtCO_2$/yr (rounded) – Base Case

CCS requirement to comply with EU ETS regulation	2020		2025		2030			
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Skewness	Kurtosis
Cement Sector CCS requirement	0	0	0	0	0	1	22.25	533.21
Chemicals Sector CCS requirement	0	0	1	3	2	4	5.26	35.30
Iron & Steel Sector CCS requirement	0	0	9	12	14	18	1.12	3.33
Petroleum & Gas CCS requirement	0	0	0	1	0	2	10.23	117.70
Power Sector CCS requirement	0	1	8	7	67	50	0.65	2.22
Total CCS requirement	0	1	17	21	83	68	0.91	3.19

Although the average deployment level is highest in the power sector, its standard deviation is also the highest (see Table 2.3). Furthermore, the kurtosis statistic indicates that the power sector probability distribution is the flattest. This indicates that investment uncertainty is most pronounced in the power sector.

2.3.2.3. CCS DEPLOYMENT BY TECHNOLOGY TYPE

Table 2.5 outlines the forecasted scope for CCS deployment by technology type. In 2020, no deployment of CCS is expected, possibly with the exception of newly built gas-fired power plants although their deployment is in any case little and likely to be zero. In 2025, the increased scarcity of allowances leads to higher average deployment levels in the power,

Table 2.4: Percentiles of deployment in 2030 in $MtCO_2$/yr (rounded) – Base Case

Percentile	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Cement Sector	0	0	0	0	0	0	0	0	0	13
Chemicals Sector	0	0	0	0	0	0	1	1	3	42
Iron & Steel Sector	0	0	0	0	0	14	17	33	38	76
Petroleum & Gas Sector	0	0	0	0	0	0	0	0	0	31
Power Sector	14	28	28	38	52	69	94	120	152	235
Total requirement	14	28	29	39	58	86	117	149	191	397

Table 2.5: CCS Deployment differentiated by type in $MtCO_2/yr$ (rounded) – Base Case

Technology / t	2020		2025		2030			
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Skewness	Kurtosis
Cement - Post Combustion new build	0	0	0	0	0	0	15.16	257.07
Cement - Post Combustion retrofit	0	0	0	0	0	0	25.76	664.67
Chemicals – Ammonia new build	0	0	0	0	0	0	5.81	38.91
Chemicals – Ammonia retrofit	0	0	0	1	0	1	5.31	35.70
Chemicals – Direct energy new build	0	0	0	0	1	1	3.84	22.66
Chemicals – Direct energy retrofit	0	0	1	3	1	3	5.27	34.21
Iron & Steel – CCS new build	0	0	3	3	8	9	0.75	2.42
Iron & Steel – CCS retrofit	0	0	6	9	6	10	1.49	4.13
Petroleum & Gas – Downstream CCS	0	0	0	1	0	2	10.23	117.70
Power – Biomass CCS new build	0	0	0	0	0	2	24.31	611.30
Power – Coal CCS new build	0	0	2	4	38	43	0.88	2.30
Power – Coal CCS new build with Enhanced Oil Recovery (EOR)	0	0	1	0	5	1	-2.90	10.31
Power – Coal CCS retrofit	0	0	4	2	19	6	-2.26	6.79
Power – Gas CCS new build	0	1	0	1	0	1	2.25	6.13
Power – Gas CCS new build with EOR	0	0	0	0	7	4	-0.70	1.60
Power – Gas CCS retrofit	0	0	0	0	0	0	21.24	511.57

chemical, iron & steel sectors, with the cement sector being a notable exception. The highest deployment levels are found for newly built and retrofitted coal-fired power plants, as well as for newly built and retrofitted plants in the iron & steel sector. By 2030, a similar but more pronounced pattern is visible as a result of continued average allowance shortages and decreasing marginal costs of deployment.

2.3.2.4. THE ROLE OF UNCERTAINTY

The standard deviations in Tables 2.3 and 2.5 reveal that the macro-level uncertainty, originating from allowance demand volatility, has a considerable impact on the scope for

CCS. Sources of uncertainty, besides allowance demand volatility, have not been taken into account. As a result, the confidence intervals are an indication of the ability of the ETS to drive investments in abatement technologies: the larger the confidence interval, the greater the investment uncertainty for investors and the lower the abatement impact of the ETS.

2.3.3. Sensitivity Analysis

In this section, the sensitivity of the results to key assumptions and currently proposed adjustments to ETS regulation is tested and compared to the base case (Scenario 1.0).

First of all, the stock of banked allowances that has been built up since 2008 is likely to have an impact on the scope for CCS. Banked allowances provide degrees of freedom to the industry, and thus may reduce the need for immediate abatement. Scenario 1.1 tests the case in which no CDM credits are allowed after 2020 ($LD_t = 0$ after 2020, see Equation 2.1).

In Scenario 1.2, the potential effect of a much more stringent allowance allocation regime is tested. An amendment to that end, *e.g.* implying an increased linear reduction rate of 2.25% per annum (up from 1.74%) starting in 2013, was proposed by the European Parliament Environment Commission in December 2011. If the amendment were to be accepted, it would lead to reduced allowance supply until 2030 by approximately 2.2 billion allowances.

In Scenario 1.3, we test a scenario assuming that only 50% of the nuclear power potential is available ($^1/_2\, TAC_t^{k=nuclear}$, see Equation 2.11). In the wake of the Fukushima meltdown in March 2011, public and political support for nuclear energy production has decreased. As a result, alternative abatement options have become scarcer, thereby increasing the scope for CCS.

Table 2.6: Summary sensitivity analysis

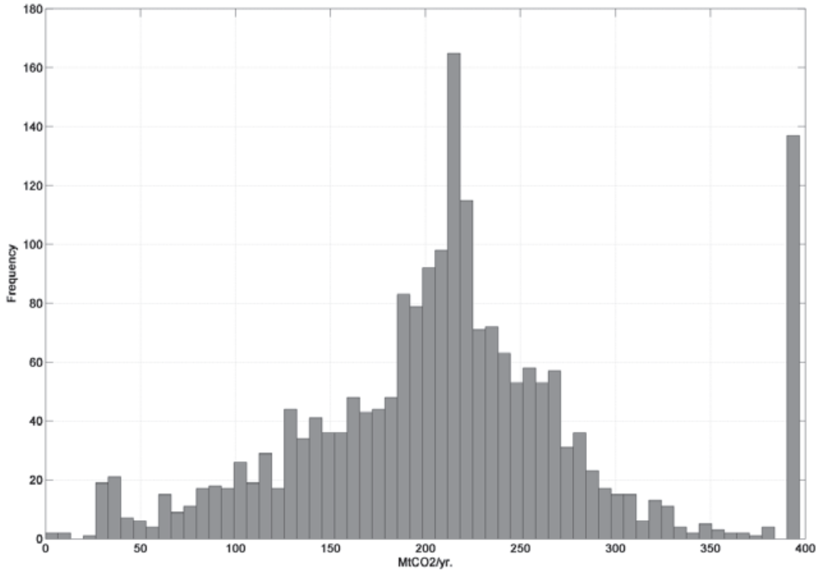
Scenario	**Output Parameter**	**2020**	**2025**	**2030**	**2030Δ**
1.0: Base Case (The Base Case)	Mean Cumulative Abatement (MtCO$_2$)	219	385	601	-
	Fundamental Carbon Price Indicator (€)	31	45	38	-
	Mean/Median CCS requirement (MtCO$_2$/yr)	0 / 0	17 / 6	83 / 58	-
	Stdev CCS requirement (MtCO$_2$/yr)	1	21	68	-
	Probability of non-compliance (%)	0	0	0	-
1.1: BC EG + No CDM after 2020 (The Base Case economic growth assumptions, but no CDM linking after 2020)	Mean Cumulative Abatement (MtCO$_2$)	218	465	705	+104
	Fundamental Carbon Price Indicator (€)	31	60	46	+8
	Mean/Median CCS requirement (MtCO$_2$/yr)	0 / 0	37 / 41	135 / 133	+52/+75
	Stdev CCS requirement (MtCO$_2$/yr)	1	27	80	+12
	Probability of non-compliance (%)	0	0	1	+1
1.2: BC EG + EP Amendment (The Base Case economic growth assumptions, but -2.25% linear cap reduction)	Mean Cumulative Abatement (MtCO$_2$)	283	484	767	+166
	Fundamental Carbon Price Indicator (€)	47	63	54	+16
	Mean/Median CCS requirement (MtCO$_2$/yr)	1 / 0	41 / 48	175 / 187	+92/+129
	Stdev CCS requirement (MtCO$_2$/yr)	3	28	77	+9
	Probability of non-compliance (%)	0	0	3	+3
1.3: BC EG + Low Nuclear Potential (The Base Case economic growth assumptions, 50% of nuclear potential)	Mean Cumulative Abatement (MtCO$_2$)	211	372	591	-10
	Fundamental Carbon Price Indicator (€)	35	49	43	+5
	Mean/Median CCS requirement (MtCO$_2$/yr)	0 / 0	22 / 13	109 / 101	+26/+43
	Stdev CCS requirement (MtCO$_2$/yr)	2	24	76	+8
	Probability of non-compliance (%)	0	0	0	+0
1.4: BC EG + No CDM + EP Compromise + Low Nuclear Potential (BC EG + compromise on ETS correction + other restrictions in Scenarios 1.1 & 1.3)	Mean Cumulative Abatement (MtCO$_2$)	245	497	775	+174
	Fundamental Carbon Price Indicator (€)	44	69	58	+20
	Mean/Median CCS requirement (MtCO$_2$/yr)	1 / 0	58 / 59	213 / 214	+130/+156
	Stdev CCS requirement (MtCO$_2$/yr)	2	26	79	+11
	Probability of non-compliance (%)	0	1	7	+7
2.0: Double Dip (Carbon output falls by 7% in 2013 following a big economic shock)	Mean Cumulative Abatement (MtCO$_2$)	138	297	503	-98
	Fundamental Carbon Price Indicator (€)	14	30	31	-7
	Mean/Median CCS requirement (MtCO$_2$/yr)	0 / 0	5 / 5	43 / 28	-40/-30
	Stdev CCS requirement (MtCO$_2$/yr)	0	9	46	-22
	Probability of non-compliance (%)	0	0	0	+0
2.1: DD EG + No CDM after 2020 (Double Dip economic growth assumptions and no CDM linking after 2020)	Mean Cumulative Abatement (MtCO$_2$)	137	387	601	+0
	Fundamental Carbon Price Indicator (€)	14	47	39	+1
	Mean/Median CCS requirement (MtCO$_2$/yr)	0 / 0	16 / 6	81 / 61	-2/+3
	Stdev CCS requirement (MtCO$_2$/yr)	0	18	63	-5
	Probability of non-compliance (%)	0	0	0	+0
2.2: DD EG + EP Amendment (Double Dip economic growth assumptions and -2.25% linear cap reduction)	Mean Cumulative Abatement (MtCO$_2$)	209	407	669	+68
	Fundamental Carbon Price Indicator (€)	28	52	48	+10
	Mean/Median CCS requirement (MtCO$_2$/yr)	0 / 0	19 / 14	121 / 123	+38/+65
	Stdev CCS requirement (MtCO$_2$/yr)	0	19	69	+1
	Probability of non-compliance (%)	0	0	0	+0
2.3: DD EG + Low Nuclear Potential (Double Dip economic growth assumptions and 50% of nuclear potential)	Mean Cumulative Abatement (MtCO$_2$)	138	297	502	-99
	Fundamental Carbon Price Indicator (€)	17	36	37	-1
	Mean/Median CCS requirement (MtCO$_2$/yr)	0 / 0	8 / 5	66 / 38	-17/-20
	Stdev CCS requirement (MtCO$_2$/yr)	0	12	59	-9
	Probability of non-compliance (%)	0	0	0	+0
2.4: DD EG + EP Compromise + No CDM + Low Nuclear Potential (DD EG + compromise on ETS correction and other restrictions from Scenario 2.1 & 2.3)	Mean Cumulative Abatement (MtCO$_2$)	170	428	679	+78
	Fundamental Carbon Price Indicator (€)	24	60	51	+13
	Mean/Median CCS requirement (MtCO$_2$/yr)	0 / 0	34 / 36	158 / 172	+75/+114
	Stdev CCS requirement (MtCO$_2$/yr)	0	25	69	+1
	Probability of non-compliance (%)	0	0	0	+0

Finally, a combination of all measures is tested in Scenario 1.4. However, because we consider the 2.25% linear reduction of the allowance cap (that was tested in Scenario 1.2) to be ambitious and therefore likely to face serious political opposition on the European level as well as the member-state level, it is replaced by a political compromise alternative. The compromise entails an increased linear reduction rate of 2% per annum (up from 1.74%) starting in 2013. Scenario 1.4 thus combines a strong reduction of allowance allocation and a reduction of a prominent abatement alternative to CCS.

All scenarios have been tested twice. The second round of Scenarios (2.0 to 2.4) assumes that the economy ends up in an economic 'double-dip' in 2014. A 'double dip' here means that we assume that the emission level falls by 7% in 2014 and will recover by a 2% increase in 2015. This pattern resembles the 2009-2010 period. Emissions under the EU ETS dropped by more than 11% in 2009 following the financial and economic crisis that initiated in late 2008 (EC, 2010) and recovered around 3% one year later (EC, 2011). The fall and slight recovery of the emission level over the 2009-2010 period was already accounted for in the Base Case. By assuming a similar, yet slightly less pronounces emission growth pattern over the years 2014-2015, we implicitly account for the possibility of another economic shock that leads to a net fall in the emission output.

Table 2.6 shows that the scope for CCS increases substantially if allowance supply is restricted. As the same time, lower availability of nuclear power generation drives up average marginal abatement costs (€43 in 2030) and the average requirement for CCS (109 $MtCO_2$/yr). The combination of all restrictions (in Scenario 1.4) increases the mean CCS requirement in 2030 to 213 $MtCO_2$/yr, up from 83 $MtCO_2$/yr in the Base Case. The standard deviation of CCS requirement increases strongly in Scenarios 1.1-1.4 compared to the Base Case, which signals an increase in underlying uncertainty of CCS deployment. The latter

Figure 2.11: Total deployment of CCS in 2030 (in MtCO₂/yr) – Scenario 1.4



increase can be explained by the fact that firms which hold a relatively expensive CCS potential and previously did not have to consider an investment, now face investment uncertainty under a tightened cap.

In Scenarios 1.2 and 1.4, the probability of non-compliance increases from 0% in the Base Case to a modest 3 and 7 percent respectively.

Scenarios 2.0-2.4 show that the impact of allowance supply restrictions on the FCPI and the requirement of CCS can be largely undone by assuming a short ‘double-dip’ during 2014-2015.

The standard deviations of CCS requirement are lower in Scenarios 2.0-2.3, because the ‘double-dip’ lowers the probability that medium to high-cost CCS alternatives will be activated by the EU ETS, or that firms will be forced into non-compliance.

Scenario 1.4 provides the largest scope for CCS. The probability distribution of the total level of deployment according to this scenario is shown in Figure 2.11, with an average deployment level of 213 $MtCO_2$/yr. Furthermore, the peak on the outer-right of the distribution in Figure 2.11 shows that there is a 7% probability of full deployment. Full deployment of all available abatement technology is linked to non-compliance. Non-compliance results when the allowance supply regime is so strongly restricted that firms lack sufficient abatement opportunities or banked allowances to comply with ETS regulation (hence all abatement capacity that *is* available is deployed). The peak thus signals that the simulated ETS regime may seriously constrain the firms that are covered by the scheme. In reality, firms may also choose to lower their production levels, or move their production facilities to a less regulated country. Such responses are not modelled here, yet they would anyhow imply that firms would be under significant stress via the EU ETS.

2.4. Discussion

Direct comparison of the results presented above with forecasted CCS deployment rates in other studies (*e.g.* Odenberger *et al*., 2008*;* Broek *et al.*, 2010; Odenberger and Johnson, 2010; Broek *et al.*, 2011; IEA, 2011) is difficult, due to the large differences in approach and assumptions, as well as in geographical, sectoral and technical scope. However, the results in the previous section seem to suggest, on average, a smaller scope for CCS across all sectors until 2030 than found in the above studies. For example, Odenberger *et al.* (2008) projected a 2030 CCS deployment rate of approximately 300 $MtCO_2$/yr in the electricity sector in Northern Europe alone (Germany, UK, Denmark, Finland, Sweden and Norway), while Broek *et al.* (2010) estimated a capture rate of approximately 95 $MtCO_2$ per annum in the Netherlands by 2030 (about 40 $MtCO_2$/yr of which was to be imported from German and

Belgian sources). Moreover, in our study, CCS deployment is expected to fall short of the IEA estimates for industrial sectors (excluding the power sector). In their BLUE Map scenario, IEA (2011) expects that by 2030 a deployment of roughly 100 $MtCO_2$/yr will be required in OECD Europe, while we find a deployment in industrial sectors of around 16 $MtCO_2$/yr.

More importantly, the results in this study indicate that a simple average, or deterministically determined, deployment rate provides a biased perspective on the future scope for CCS in Europe. Averages do not reveal the inherent uncertainty for CCS which is related to Europe’s key incentive mechanism: the EU ETS. Marginal or no CCS deployment is possible in case of low future economic growth, while maximum deployment is also possible if firms are forced into non-compliance. These results underline how the interaction between EU ETS fundamentals ultimately drives the carbon price and CCS deployment, leaving investors with a rather uncertain investment perspective.

Therefore, if CCS is to be a key abatement technology in Europe, policymakers should focus on making the EU ETS more robust against allowance demand uncertainty. By introducing measures to stabilize or smooth allowance demand over time, single-digit carbon prices, as well as non-compliance, can possibly be avoided, thereby providing some level of certainty to investors. Furthermore, although it has been outside the scope of this study, the benefits of improved investment certainty will likely accrue to all firms under the scheme, and will not be limited to those considering investments in CCS. In any case, under the current EU ETS regime, waiting for the carbon price to temporarily reach the required level to trigger deployment does not seem to be a viable long-term strategy.

2.5. Conclusions and Policy Implications

So far, most modelling work on CCS deployment seems to have a positive bias towards the effectiveness of the EU ETS as a driver for deployment. The reasons for that are that most CCS-based economic modelling uses a deterministic approach and disregards interactions between technology deployment and incentives. Furthermore, qualitative obstacles to the introduction of CCS, such as societal acceptance issues, organizational complexities or other societal factors that may slow down learning rates, are often neglected.

In this study, we have tried to take the CCS deployment analysis one step further by designing a stochastic, interactive model of the EU ETS system. Such a model enables us to simulate CCS deployment in the period until 2030 under a number of assumed EU ETS policy regimes and macro-economic conditions.

The results show that the considerable investment uncertainty under the EU ETS makes it doubtful that the EU ETS is as efficient in driving abatement investments as it is often assumed to be. This is particularly important as investments in CCS technology involve high sunk costs, lead times and an operational lifetime that often spans multiple decades. Therefore, in order to efficiently plan such investments, investors generally are rather sensitive to the level of certainty market incentives can provide them with about patterns of future CO_2 penalties. Simulations based on our model suggest that the EU ETS cannot offer that certainty as future ETS allowance prices are volatile and highly responsive to parameter changes. This problem especially applies to the power sector, which faces the highest levels of uncertainty regarding required deployment levels of CCS under the EU ETS.

From a policy perspective, the results suggest that priority should be given to measures that could make the scheme more robust against economic and policy uncertainty. Current proposals primarily focus on trying to increase overall *levels* of allowance prices by limiting the supply of allowances in one way or another. Our results show that on average EU ETS allowance prices may tend to increase within a couple of years, albeit consistently with extremely high levels of uncertainty. To illustrate the latter, a single-year serious[12] overall economic setback in Europe will largely undo the emission reduction impact of a fairly 'aggressive' policy mix that significantly reduces the allowance allocation levels.

Our results also show that the fundamental problem with the EU ETS effectiveness in enhancing abatement investment is its inherent *uncertainty* on both the long and short term with regard to the need for abatement and the level of the carbon price.[13] Reducing such uncertainty is not easy but would anyhow require measures that try to stabilize the CO_2 price and demand for allowances, rather than interfering with the allowance allocation regime.

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[12] *I.e.* a one year drop in emission levels by 7%. Note that the emission reduction in 2009 was about 11%.

[13] In fact, our results suggest that the current fundamental non-scarcity of EU ETS allowances will turn into a scarcity situation within a limited number of years, from then on driving up the EU ETS prices to still volatile but higher price levels.

3. INTERACTION BETWEEN EU INSTRUMENTS AND MEMBER-STATE INSTRUMENTS: THE END OF CO_2 EMISSIONS TRADING IN EUROPE?

3.1. Introduction

Member states of the European Union have chosen to cap CO_2 emissions from installations of a large number of energy-intensive sectors via the European Union Emissions Trading Scheme to ensure that collective long-term emissions-reduction goals are achieved. Theoretically, the market-based character of the EU ETS should guarantee that the emission target is achieved in a least-cost manner. However, such a least-cost solution is possible only if outside interference with the allocation via the EU ETS market scheme is avoided (Böhringer *et al.*, 2008). Interestingly, European policy makers themselves are likely to be a source of outside interference by introducing many instruments for CO_2 abatement on a national, or even regional and local, level alongside the EU ETS. Many of those parallel instruments are introduced in pursuit of domestic energy and climate targets (EEA, 2011a; Lundberg *et al.*, 2012). Examples include power-plant performance benchmarks, feed-in tariffs for renewables, and biomass co-firing mandates. Parallel instruments can have local benefits for the national government that introduces the instrument, such as employment benefits or stability of electricity supply (Sorrell and Sijm, 2003; Bennear and Stavins, 2007). However, with respect to carbon abatement, parallel instruments are direct substitutes for the EU ETS. The abatement achieved through parallel instruments reduces the demand for EU ETS carbon allowances and lowers the carbon price, thereby reducing the amount of abatement that is triggered by the EU ETS. Building on this logic, the aggregate impact of all parallel instruments across Europe could significantly lower the carbon allowance price and increase the societal costs associated with CO_2 abatement. At an extreme, parallel instruments could make the EU ETS completely redundant, permanently driving the CO_2 allowance price down to zero.

Since 2005, the EU ETS carbon price has generally been rather low and volatile. The weak performance of the EU ETS is typically attributed to negative and/or stagnating economic growth since 2008, in combination with a too generous allowance allocation regime. The potential role of parallel instruments is not well understood in this context. Yet such knowledge is needed in order to formulate the right policy response, *e.g.* if policy makers are interested in strengthening the EU ETS. In fact, greater knowledge of the effects of multiple parallel instruments on the performance of the EU ETS can be part of the solution to raise its effectiveness. As long as policy makers are unaware of the costs associated with parallel instruments in the form of reduced ETS performance, they may be inclined to spend more than the socially optimal amount on parallel instruments alongside the EU ETS. Closing this information gap could be an important step toward a more cost-efficient and goal-oriented CO_2 mitigation policy design.

Although a deep understanding of the effect of the whole range of parallel instruments on the performance of an emissions trading scheme can be highly valuable to policy makers, the focus of existing literature has been largely limited to interactions between an ETS and a single other parallel instrument. Studying the aggregate effect of multiple parallel instruments would allow for a more comprehensive sensitivity analysis of the EU ETS and would obviously represent a more realistic policy setting. In this chapter, the intention is to add to the literature by empirically examining the performance of the EU ETS within a policy setting with multiple parallel instruments. As will be explained in more detail below, we aim to provide benchmarks to policy makers that can be used to assess the potential adverse effect of proposed parallel instruments on the performance of the EU ETS.

In the analysis, we distinguish between two broad categories of parallel instruments: Type 1 and Type 2 instruments. Both types lead to a reduction of emissions in ETS sectors, but they do so in different ways. Type 1 parallel instruments are defined as instruments that provide *ETS sectors* with incentives to adopt low-carbon technology. Thereby, Type 1 incentives lower the carbon intensity of production in ETS sectors. An example of a Type 1 instrument is a subsidy to invest in biomass co-firing in existing coal-fired power plants. Type 2 instruments are defined as instruments that provide incentives to *non-ETS sectors* (*e.g.* households) to lower their demand for products from ETS sectors. In that manner, Type 2 instruments lower the required production level in ETS sectors and the associated CO_2 emissions. Two examples of Type 2 instruments are incentives for deployment of decentralized renewable electricity generation capacity and subsidies to improve the energy efficiency of households. Both Type 1 and Type 2 instruments have been introduced on a relatively large scale across Europe. A few examples of both types of instruments that are currently in force are provided in Table 3.1. All the examples in the table have been introduced since 2008.

To study the effect of both, Type 1 and Type 2, instruments on indicators of the performance of the EU ETS, we use the dynamic stochastic simulation model of the EU ETS that was developed in Chapter 2. The model incorporates year-to-year economic growth uncertainty. The performance of the EU ETS is known to be highly dependent on economic growth rates: high economic growth rates force firms to invest heavily in CO_2 abatement to remain below the CO_2 allowance cap and provide upward pressure for the carbon price, whereas the carbon price and the need to invest in CO_2 abatement is significantly lower if economic growth rates fall below average. Incorporating both parallel instruments and economic growth uncertainty into the analysis makes it possible to examine their relative importance.

We put particular emphasis on assessing under what conditions the EU ETS becomes redundant, as this redundancy provides a clear benchmark for policy makers. EU ETS redundancy is defined here as a situation in which parallel instruments trigger enough abatement activity to permanently (at least until the end of our modelling horizon) drive the EU ETS carbon price to zero. If it is assumed that policy makers have knowledge about the expected local abatement effects of a proposed parallel instrument, the threshold level enables policy makers to assess the relative EU-ETS-undermining effect of the proposed parallel instrument. In that manner, policy makers are better informed about the potential cost and impact of their national policy initiatives alongside the EU ETS.

Table 3.1: Examples of Type 1 and Type 2 instruments that reduce ETS sector emissions since 2008 across Europe

Type 1		**Type 2**	
Instruments aimed at ETS sectors: reduce carbon intensity of production in ETS sectors		*Instruments aimed at non-ETS sectors: reduce production levels in ETS sectors*	
Austria (2012)	Ökostromverordnung – FITs for biomass co-firing (0.0612 EUR/kWh).	Austria (2012)	Ökostromverordnung – FITs for renewable energy.
Netherlands (2009)	Agreement on energy efficiency for ETS companies (MEE) – Negotiated agreement that forces ETS firm to aim for energy efficiency improvement.	Netherlands (2011)	SDE+ - Provides a feed-in subsidy to installations according to generation costs on a first come first served basis.
Germany (2012)	CHP Agreement with Industry – Agreement between German Government and the industrial sector to improve energy efficiency in the industrial sector. Objective: raise energy efficiency by 1.3% annually.	Germany (2011/2012)	2011 – Energy Efficiency Fund – Fund of more than €100 million to promote energy efficiency across end-use sectors. 2012 - Up to 30% financial allowance for investments in cross sectional technology that increases energy efficiency (*e.g.* heat pumps and air-conditioning). 2012 - Amendment of EEG – Feed-In Tariffs (FITs) for non-ETS renewables.
Italy (2008)	Decree on Implementation of EU Energy Services Directive – Includes setting up a White Certificate Scheme in the energy industry.	Italy (2012)	Ministerial Decree – Incentives for increased energy efficiency in existing buildings, totalling €200mln in subsidies.
Poland (2008)	Long-term Programme for Promotion of Biofuels or Other Renewable Fuels – Provides support for biomass co-firing through arrangements that improve cost-effectiveness of biomass supply-chain.	Poland (2011)	Energy Efficiency Act – Introduces a White Certificate Scheme imposed on utility companies that promote energy efficient behaviour of customers.
Portugal (2008/2010)	2008 - Management System of Intensive Energy Consumption – Binding energy audits for energy intensive facilities (>500 toe/yr) with a 6-8 year interval. Facility operators have to set energy and carbon intensity targets. After approval by government, penalties can be issued for missing the target. 2010 - Implementation of CHP Directive – Provides financial remuneration for high efficiency and renewable based electricity generation in CHP plants.	Portugal (2010/2013)	2010 - Tax Deduction for Efficient Equipment – Tax deductions on investments in efficient equipment that improve the thermal performance of buildings. 2013 – Feed-in tariffs for micro and mini generation for 2013 – Includes feed-in tariff for mini (<3.68kW) and micro (3.68-20 kW) solar PV for 15 years: first 8 years 0.196 EUR/kWh, following 7 years 0.165 EUR/kWh.
Spain (2008)	Voluntary Agreements 2008-2012 – Promotes adoption of energy saving measures by industry. Financing lines are available, with preferential treatment for formally committed firms.	Spain (2013)	PIMA SOL – program to promote GHG reduction in the tourism sectors via, amongst others, reduced energy consumption.
Sweden (2010)	Energy Audit for Companies – provides support for 50% of costs of an energy audit for companies using more than 500 MWh/yr. Measures follow a few years later.	Sweden (2010)	Government subsidies for Local Energy Efficiency Measures - ~€11 million annually for local municipalities and county councils to undertake energy efficiency measures.
UK (2010)	National Renewable Energy Action Plan – Includes Renewable Obligation Certificates (ROC) to subsidize biomass-co-firing.	UK (2010)	CRC Energy Efficiency Scheme – Targets large private and public sector organisations and caps their emissions.

Source: IEA Policies and Measures Database (http://www.iea.org/policiesandmeasures/)

3.2. Literature review

The study of interacting policy instruments has its roots in the work of Tinbergen (1952, 1956), who formulated general rules for the controllability of an economic system. He coined the rule that the number of independent instruments must equal the number of independent targets in order for a solution to exist. Theil (1954, 1956, 1964) extended the work of Tinbergen to other situations, including those in which the number of instruments is lower than the number of targets. The analysis in this chapter concerns the reverse situation: an over-determined system with more instruments than targets. On top of that, multiple governments govern the instruments, while the EU ETS is an instrument shared by all thirty-one governments. Over-determined systems have many solutions, although such a solution may be hard, if not impossible, to attain in practice. Finding a solution requires strong coordination by a central planner. That planner should set all excess instruments at arbitrary fixed values, while having full information regarding the relations (or lack thereof) among instruments, targets, and the response behaviour of the private sector. Without a social planner or full information, a solution becomes indeterminate and uncontrollable for all governments involved (Di Bartolomeo *et al.*, 2011; Acocella *et al.*, 2012).

A set of interacting instruments and targets can become so complex that retaining control over them becomes an issue in itself for policy makers (Wildavsky, 1979). Majone (1989) defines *policy space* as a set of policies that are so closely interrelated that it is not possible to give useful descriptions of one of them or to make analytic statements about one of them without taking the others into account. Majone builds on Wildavsky's work by pointing out that policy makers tend to lose control over the policy space over time. As the number of policies grows relative to the size of the policy space, policies logically become more interdependent and interfere with other policies. At an extreme, new programs and institutional arrangements may be required to prevent or reduce the unwanted consequences of a congested policy space.

Bye and Bruvoll (2008) suggest that policy development in the energy and environmental domain has already resulted into an over-congested policy space. Concluding that little is known about the aggregate effect of environmental instruments, they call for coordination and simplification of policy tools before new instruments are added to the policy space.

To the extent that policy interactions have been analysed within the environmental domain, the primary focus has been on interactions between an emissions trading scheme and a scheme that supports the deployment of renewable electricity technologies. Much of this work has focused: on the expected changes in the prices (Boots, 2003; Rathmann, 2007) and on the supply of electricity (Anandarajah and Strachan, 2010), on welfare implications (Böhringer *et al.,* 2008), on the CO_2 price (Hindsberger *et al.*, 2003), and on levels of CO_2 emissions (Morthorst, 2003). See Del Rio (2007) for a review of the literature. Fewer authors have considered highly congested policy spaces, although such analyses would probably help to uncover and avoid unintentional consequences of congestion. In what follows, we will highlight some notable papers in which a more congested policy space has been considered.

Oikonomou and Jepma (2008) designed a qualitative framework to identify potential interactions between combinations of various climate policy instruments. Their framework builds on, and summarizes, interactions that have been identified in previous literature, departing from findings of the INTERACT project (Interact, 2003). The framework helps policy makers to classify potential positive and negative interactions between sets of instruments. Kautto *et al.* (2012), using the existing literature and interviews with experts, analysed changes in the use of biomass as a result of the introduction of the EU ETS and its interactions with parallel instruments in seven EU countries. Although Kautto *et al.* (2012) had difficulty attributing observed effects to specific instruments, they noted that the EU ETS probably had amplified the effects of existing policies. In some cases the introduction of the EU ETS triggered the introduction of additional "balancing measures" to offset biomass price effects. Sorrell and Sijm (2003) and Bennear and Stavins (2007) identified situations in which combinations of environmental instruments can be justified. Sorrell and Sijm (2003) argued that combinations of instruments can usefully coexist if they lead to an improvement of the static or dynamic efficiency of a trading scheme, or if they deliver other valuable policy objectives. Bennear and Stavins (2007) noted that multiple instruments can be justified if there have been multiple market failures, or if an exogenous constraint cannot be removed.

Although the use of multiple instruments can have benefits, it remains unclear when such combinations can lead to a loss of control by policy makers. However, one can safely assume that instruments are never introduced by policy makers with the intent to be redundant. If instruments become redundant unintentionally, it indicates that policy makers have lost control over the policy space, as Majone (1989) and Wildavsky (1979) suggested. De Jonghe *et al.* (2009) analysed the possibility of redundancy of an emissions trading scheme, albeit in a stylized theoretical setting with one parallel instrument. Employing a welfare-optimization model, they showed that if a renewables quota[14] is set above a threshold level alongside an emissions trading scheme, the CO_2 allowance price falls to zero and the ETS becomes redundant. These results, which are in line with what Hindsberger *et al.* (2003) have found,[15] seem to suggest that if policy makers set their renewables quota below a

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[14] The renewables quota is enforced through a 'green certificate' scheme. The threshold levels depends on the stringency of the emissions trading scheme.

[15] Hindsberger *et al.* (2003) examine a situation in which an international emissions trading scheme partly overlaps geographically with an international scheme of 'tradable green certificates' to stimulate the deployment of renewable energy in the Baltic Sea region. They find that the carbon price approaches zero if the renewable energy target is set sufficiently high.

threshold level, the ETS will produce a positive carbon price and contribute to carbon abatement, but this is not necessarily true in an international setting. That is, even if a national government sets a relatively low renewables quota, actions by other national governments across Europe could still drive the EU ETS beyond the threshold level and into redundancy. In fact, the introduction of a renewables quota in one country could actively trigger other governments to implement additional instruments in response to the depreciated carbon price. If such dynamics between policy-making authorities are disregarded, the probability that an ETS becomes redundant is therefore likely to be underestimated.

The likelihood of EU ETS redundancy is even greater once we take multiple sectors into account. The EU ETS covers many countries and industrial sectors and therefore interacts with a wide range of energy-related and climate-related instruments. An ETS even interacts with instruments in sectors that are not covered by the scheme (Interact, 2003). Despite these facts, literature in the field (Conrad and Kohn, 1996; Amundsen and Mortensen, 2001; Morthorst, 2001, 2003; Hindsberger *et al.*, 2003; Jensen and Skytte, 2003; Rathmann, 2007; Del Rio, 2009) not only seldom considers interaction between ETS and non-ETS sectors, but also often focuses exclusively on the electricity sector.

General-equilibrium models that cover multiple sectors typically model an emissions trading scheme that is modelled too simply to fully assess the adverse effects of parallel instruments (Morris *et al.*, 2010; Abrell and Weigt, 2008; Pizer, 2002). Allowance banking behaviour and the stochastic nature of both economic growth and CO_2 allowance demand are typically not accounted for. These factors are, however, rather important to obtain a full understanding of the effect of introducing parallel instruments alongside an emissions trading scheme (Rathmann, 2007). In this chapter, we take the above-mentioned factors into account. That is, we analyse policy interaction in an international setting, with parallel instruments in both ETS and non-ETS sectors. Also, we apply a model that accounts for important design features of the EU ETS, such as the ability to bank allowances and the role of stochastic allowance demand patterns. The model thereby reflects current EU ETS regulation. By that model specification, we aim to provide a more complete analysis of the sensitivity of the EU ETS to the introduction of parallel instruments. Specifically, we define threshold levels beyond which redundancy of the EU ETS is to be expected, assuming that knowing these threshold levels will help to better understand the real impact of their policies considered.

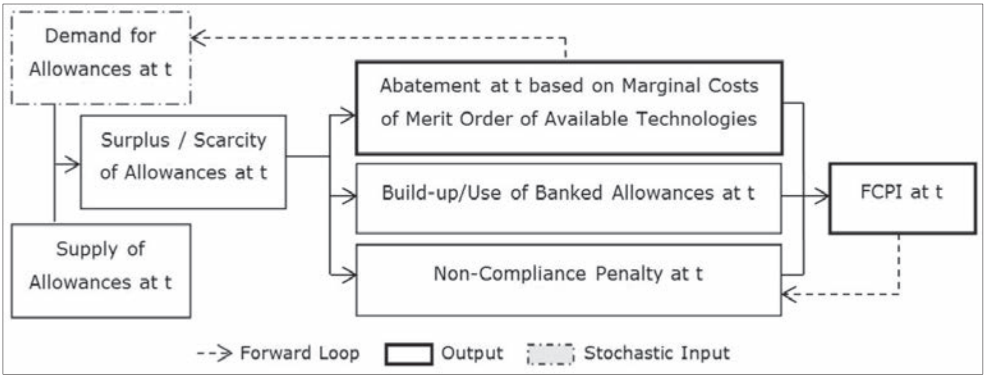
3.3. Methodology

In this section, we describe the ETS model and the manner in which parallel instruments have been introduced into it. We build on the stochastic simulation model of the EU ETS described in Chapter 2. After a short summary of the original model, we offer a detailed description of the approach used to introduce Type 1 and Type 2 instruments into the model.

3.3.1. The stochastic EU ETS simulation model

The model of the EU ETS outlined in Figure 3.1 simulates the fundamentals of the EU ETS, including annual abatement activity in various sectors and a forecast of the long-term carbon price (which we call the Fundamental Carbon Price Indicator). How the FCPI is calculated will be explained. The model runs from 2008 (the start of Phase II of the EU ETS) to 2030. The supply of allowances mirrors the current regime for allocating annual allowances. The demand for allowances is equal to business-as-usual emissions reduced by abatement that is triggered by the EU ETS. Abatement triggered by other instruments will be added to the model in a later subsection. Realized demand levels since 2008 are exogenous input to the model. Starting in 2013, the business-as-usual growth in emission is sampled

Figure 3.1: The original EU ETS model



from a distribution via a Monte Carlo procedure. The distribution is based on historical growth rates of European industrial emissions between 1990 and 2008 (EEA, 2011b).

If the supply of allowances surpasses demand, the surplus is banked for use in future years, because allowances do not expire. We assume that if the demand for allowances surpasses the supply, firms have three options available to comply with ETS regulation: investing in carbon abatement, using previously banked allowances, and paying the non-compliance penalty.[16] Paying the non-compliance penalty is treated as the option of last resort: firms will pay the non-compliance penalty only if no other banked allowances or abatement opportunities are available. In case of non-compliance, the FCPI equals the current non-compliance penalty of €100 per tonne of CO_2. Also, any remaining abatement potential and banked allowances will be utilized. In any other case, firms must choose between using banked allowances and investing in carbon abatement. Therefore, the extent to which firms choose either of the two options depends on their relative cost. An example is illustrated in Figure 3.2, which shows the equilibrium between abatement and use of banked allowances in a random year t. In that year, the overall scarcity of allowances equals 88 $MtCO_2$ and is

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[16] Carbon leakage to non-EU member countries is not included in the model.

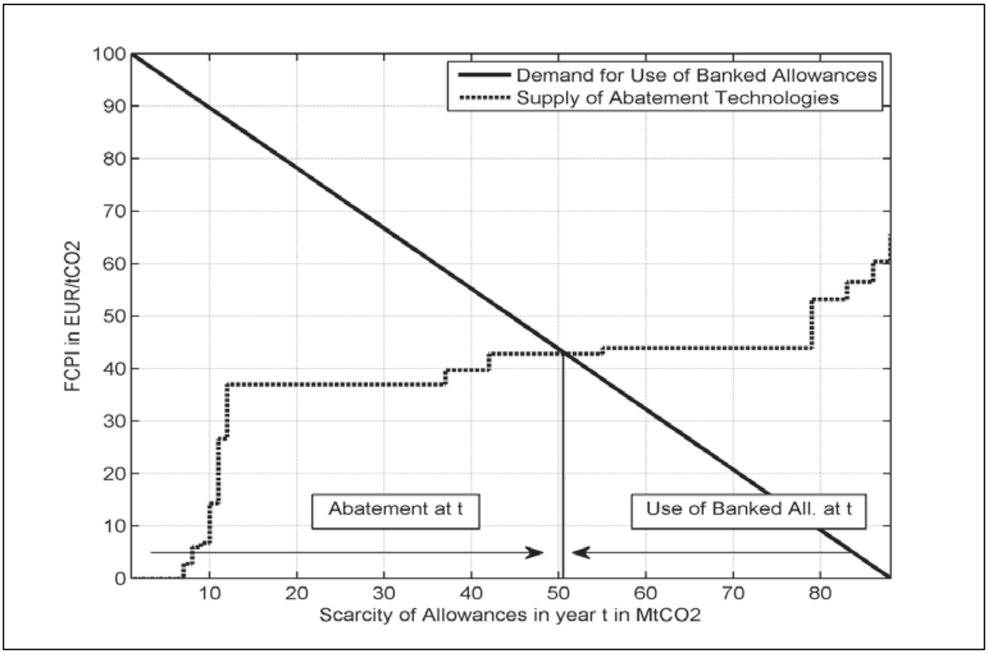
shown on the *x* axis. In equilibrium, the amount of abatement equals 51 $MtCO_2$, the use of banked allowances equals 37 $MtCO_2$, and the FCPI equals €43.

Note that we assume that firms make a minimum effort to comply with ETS regulation in order not to extract too many resources from their core business. This can be seen in Figure 3.2, as more abatement potential is available at the same marginal costs yet not all potential is used.

The curve representing supply of abatement technologies is the merit-order abatement curve. All abatement opportunities are ordered according to their relative marginal cost in euros per metric tonne abated.

The curve representing the demand for the use of banked allowances rests on the following assumptions: assume that the willingness to use banked allowances by firms at any time depends on firm-level carbon-price expectations and investment opportunities. Assume

Figure 3.2: Abatement and use of banked allowances in randomly simulated year t



also that firm-level carbon-price expectations and investment opportunities across Europe are heterogeneous, given that the population of firms under the EU ETS is highly diverse and operates under imperfect information. For example, some firms supply (hold on to) their banked allowances if the carbon price is 30 euro per tonne given their relatively low (high) price expectation in the future or access to (lack of) alternative investment opportunities with a higher expected return. Logically, the share of firms that is willing to supply their banked allowances increases as the carbon price goes up, as all firms are assumed to hold on to their banked allowances if the carbon price equals zero euro per tonne, while all firms are willing to supply their banked allowances if the market price equals the price ceiling (the non-compliance penalty). The curve representing the demand for the use of banked allowances is formed by assuming a linear relationship between these two extremes.

The equilibrium between the supply of abatement technologies and the demand for the use of banked allowances in a year determines the equilibrium FCPI in that year. The forecasted FCPI can be interpreted as a long-term forecast of the carbon price because the actual market price for carbon allowances is expected to converge to the FCPI. To understand why, consider a situation where the market price for allowances is considerably higher than the forecasted FCPI (*e.g.* due to speculation). This would trigger extra abatement activity and a reduction of demand below the equilibrium point, leading to a surplus of allowances. The surplus would put downward pressure on the carbon price, leading to convergence of the market price towards the FCPI.

Because allowance demand is uncertain, and because deployment of abatement technologies alters the shape of the merit order, a stochastic year-to-year carbon price pattern is formed. For an in-depth description of the model, see Chapter 2.

3.3.2. Introducing parallel instruments

The simulation window runs from 2008 to 2030. Within that window, we assume that parallel instruments are in place between 2013 and 2030.

3.3.2.1. TYPE 1 INSTRUMENTS

Type 1 parallel instruments are defined as instruments that lower the carbon intensity of production in ETS sectors. The common feature of these instruments is that they speed up investments in abatement technologies within ETS sectors. Introducing Type 1 instruments would affect the EU ETS, and thus would affect the ETS model, in two ways. First, allowance demand and scarcity would be reduced by the amount of abatement achieved with Type 1 instruments. Second, technologies from the merit order are used to achieve this reduction, so that this abatement potential is no longer available in future periods, thereby changing the shape of the merit order in Figure 3.2.

It is not possible to individually model all the Type 1 instruments that are in operation today. Instead, we propose a method to determine their aggregate effect on the functioning of the EU ETS. We assume that their collective impact ranges from 0 and 30 $MtCO_2$ of new abatement per year, as all relevant simulation results fall within that range.[17]

We run all possible scenarios within that range with increments of 1 $MtCO_2$. For each of these 31 scenarios the impact remains constant over time. Also, we assume in all scenarios that Type 1 instruments trigger deployment of all technologies in the merit order. For example, if Type 1 instruments are assumed to trigger a total of 10 $MtCO_2$ of new abatement per annum, the abatement potential of all technologies in the merit order is reduced proportionally until a reduction in emissions of 10 $MtCO_2$ is achieved. By reducing the

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[17] Emissions in ETS sectors were 1,898 $MtCO_2$ in 2012. Therefore, the tested range (0–30 $MtCO_2$/yr) is equivalent to abatement between 0 and 1.6 percent per annum.

abatement potential proportionately, we attempt to mirror the wide range of instruments that are in place today across industries, technologies, and abatement costs.[18]

Mathematically, the implications are rather straightforward. Allowance demand in now adjusted for the effect of Type 1 instruments:

$$AD_t^{new} = AD_t^{original} - T1_t \qquad for\ t = [2008, \ldots, 2030] \tag{3.1}$$

Here, $AD_t^{original}$ is allowance demand in year t as specified in the original model (see Equation 2.2 in Chapter 2). $T1_t$ is the reduction in demand through Type 1 instruments in year t in $MtCO_2$. If we subtract $T1_t$ from $AD_t^{original}$ we arrive at the new allowance demand in year t, AD_t^{new}.

The impact of Type 1 instruments on the merit order is defined by the following two equations:

$$\pi_t^k = \frac{TAC_t^{k,original}}{\sum_{k=1}^{n} TAC_t^{k,original}} \qquad for\ k = [1, \ldots, n], t = [2008, \ldots, 2030] \tag{3.2}$$

where π_t^i is a measure of the relative abundance of abatement technology k at t, $TAC_t^{k,original}$ is the total abatement capacity of technology k at t (in $MtCO_2$) as defined in the original model, and the denominator defines the cumulative capacity of all n abatement technologies that are available at t, and

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[18] For example, Europe is attempting to stimulate a relatively expensive technology such as CO_2 capture and storage through subsidies while efficiency improvements (which typically have a low marginal cost) also receive support via a wide range of European programs in line with the 20–20–20 targets for 2020 (EP, 2010).

$$TAC_t^{k,new} = TAC_t^{k,original} - \pi_t^k T1_t \qquad for\ k = [1, \dots, n], t = [2008, \dots, 2030] \qquad (3.3)$$

where $TAC_t^{k,new}$ is the total remaining abatement capacity of technology k in year t; that is, the original abatement capacity of technology k is diminished by $\pi_t^k T1_t$, as that proportion is assumed to be deployed through Type 1 instruments).

3.3.2.2. TYPE 2 INSTRUMENTS

Type 2 instruments are defined as instruments that reduce the production levels in ETS sectors. Type 2 instruments are primarily found in non-ETS end-use sectors. Introducing Type 2 instruments would affect the EU ETS only by reducing allowance demand in ETS sectors, because firms in these sectors face lower demand for their end products.

Similar to Type 1 instruments, we assume that the collective impact of Type 2 instruments reduces the emission level by between 0 and 30 $MtCO_2$ per annum. We run all 31 scenarios within that range with increments of 1 $MtCO_2$, while the impact remains constant over time per scenario.

Mathematically, incorporating Type 2 instruments requires adding one more term to Equation 3.1:

$$AD_t^{new} = AD_t^{original} - T1_t - T2_t \qquad for\ t = [2008, \dots, 2030] \qquad (3.4)$$

Here $T2_t$ is the reduction in the demand for allowances through Type 2 instruments in year t in $MtCO_2$.

Figure 3.3: Fundamental EUA price – Neutral Scenario

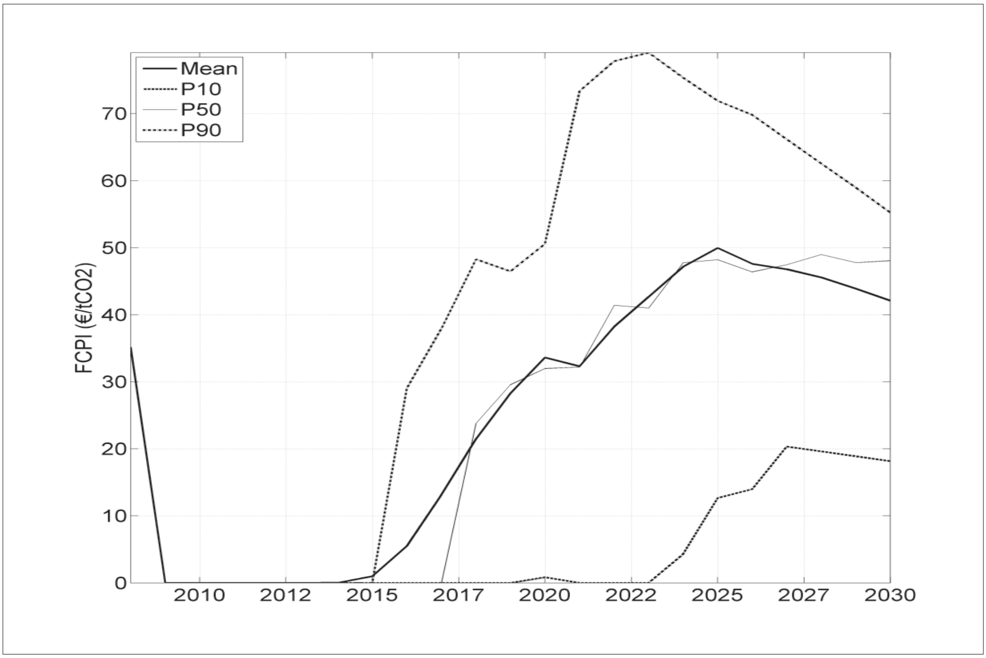
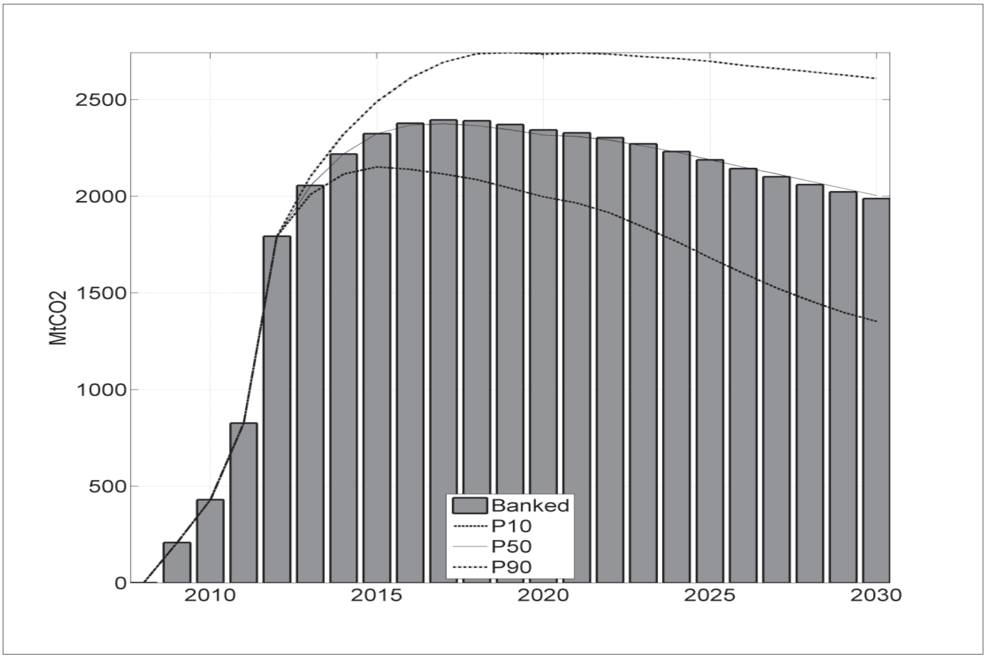


Figure 3.4: Stock of banked Allowances - Neutral Scenario



3.4. Results

As a reference, we first present results from the Neutral Scenario. In the Neutral Scenario, the ETS is the only instrument triggering carbon abatement activity; the annual impact of Type 1 and Type 2 instruments is thus 0 $MtCO_2$. In subsequent sections we examine the sensitivity of the carbon price and the emission level and the probability that the EU ETS will become redundant.

In practice, both Type 1 and Type 2 instruments operate in a parallel fashion alongside the EU ETS. Therefore, every possible quantitative combination of Type 1 and Type 2 instruments within the specified range (0–30 $MtCO_2$/yr) is tested. As a result, we run a total of 961 (31 × 31) scenarios and present results from all scenarios in three-dimensional plots.

3.4.1. The Neutral Scenario

Figure 3.3 shows that the forecasted FCPI is equal to about €35 in 2008 but plummets in subsequent years because allowances are in oversupply in those years, primarily as a result of the financial and economic crisis. In absence of speculation, the price falls to zero. Around 2015, the mean FCPI quickly increases again, up to about €50 in 2025. In the last five years of the simulation, the FCPI decreases slightly as a result of technological learning, higher prices for fossil fuel, and greater availability of abatement technologies. Because allowance demand is uncertain, there is significant uncertainty around the forecasted equilibrium level of the FCPI, as reflected by the 80 percent confidence interval in Figure 3.3. The effect of the financial and economic crisis is also clearly reflected in Figure 3.4, which depicts the overall stock of banked allowances over time. Because no end date has been specified for the EU ETS, and allowances do not expire, a positive stock of allowances remains at the end of the simulation. The stock quickly builds up after 2008, and is then gradually reduced over time towards a mean of 2,000 $MtCO_2$ worth of allowances in 2030. In case of unusually strong

Figure 3.5: Emissions under the EU ETS (in $MtCO_2$/yr)—Neutral Scenario

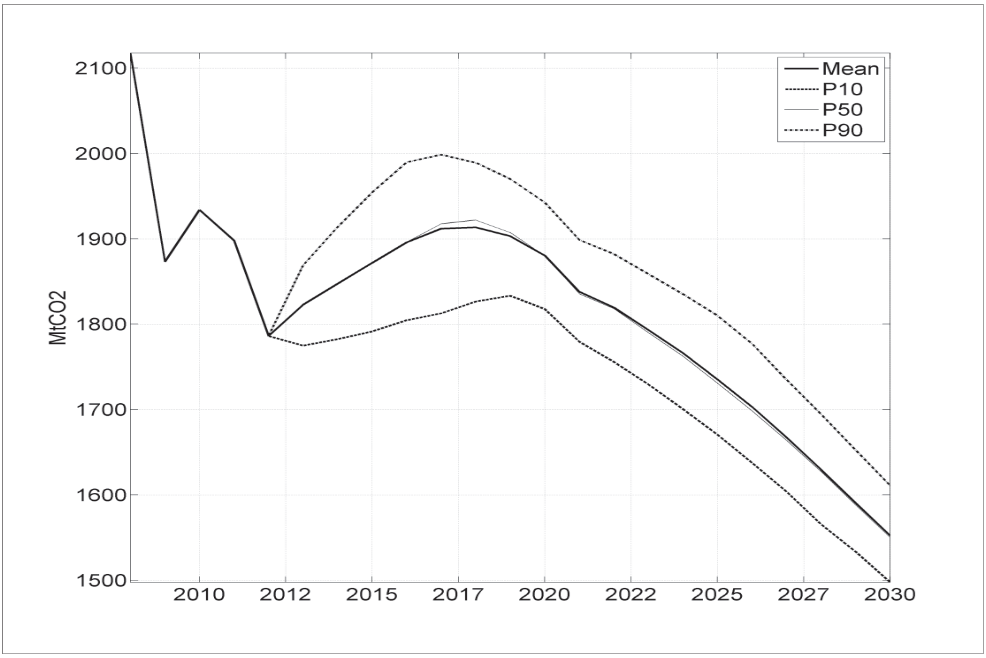


Figure 3.6: Effect of Type 1 and Type 2 instruments on the mean FCPI in 2030

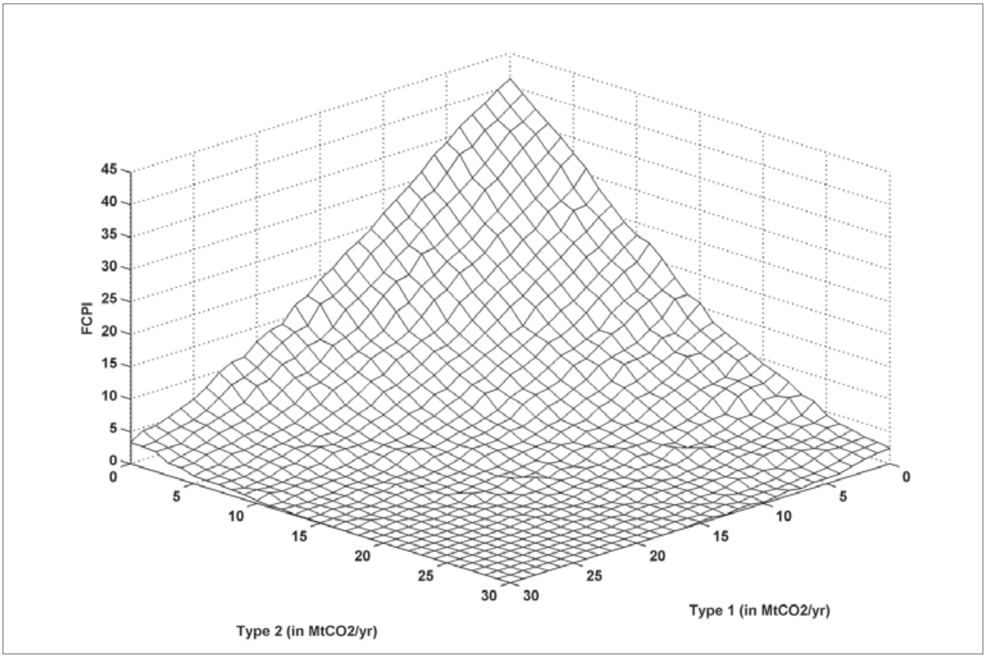


Figure 3.7: Mean and median FCPI with 0 and 20 $MtCO_2$ impact of Type 1 (Type 2 remains 0)

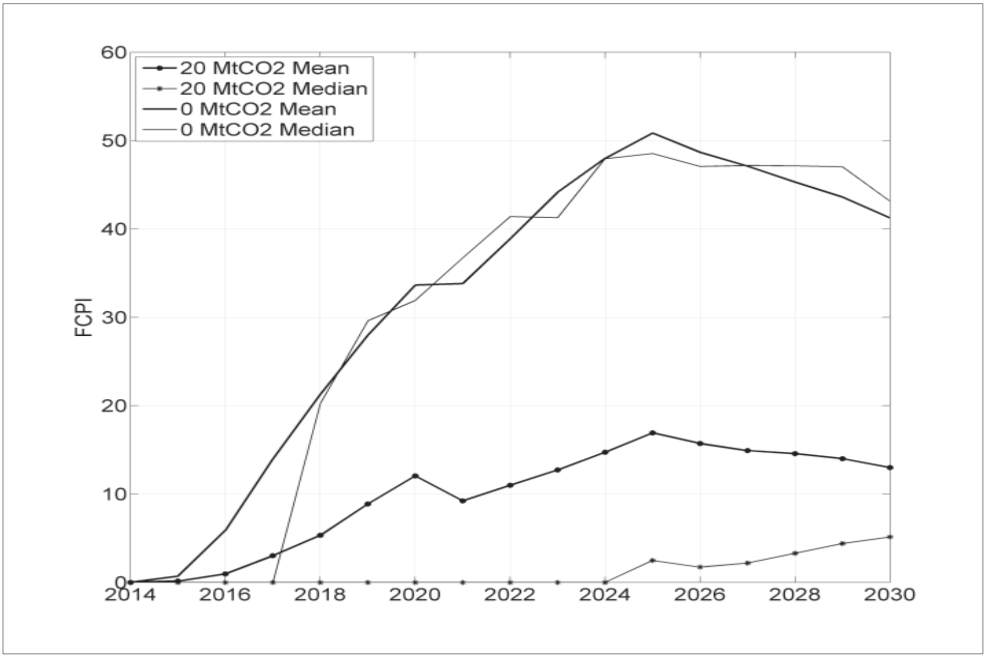
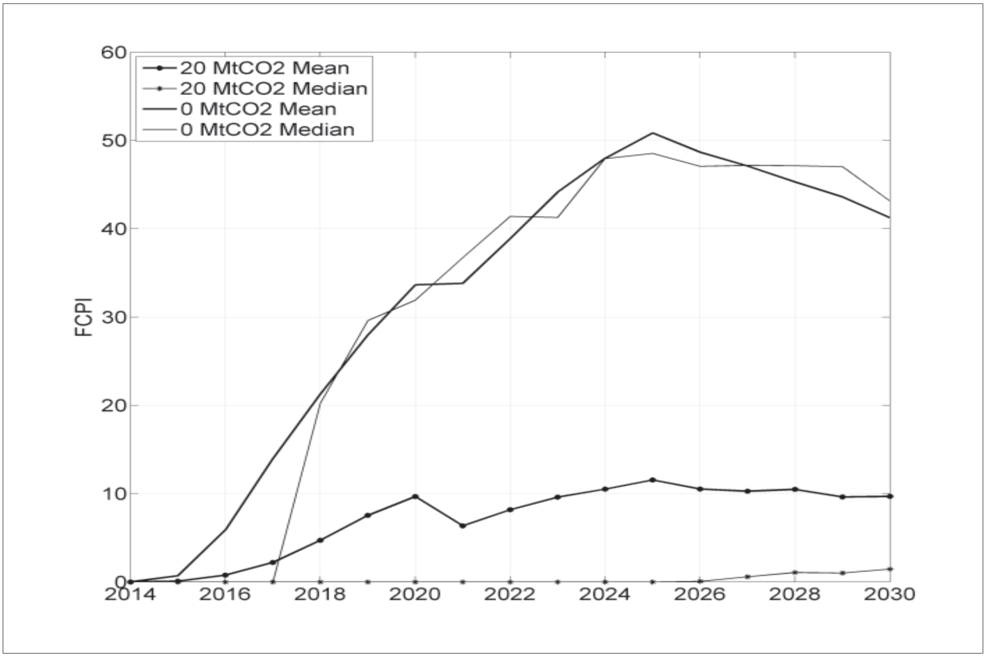


Figure 3.8: Mean and median FCPI with 0 and 20 $MtCO_2$ impact of Type 2 (Type 1 remains 0)



economic growth between 2013 and 2030, a stock level below 1,500 $MtCO_2$ also remains a possibility.

The level of emissions is depicted in Figure 3.5. Again, the effect of the economic crisis is clearly visible between 2008 and 2012. As a result, the emissions level has room to rebound until 2017. After 2017, the reduced supply of allowances forces firms to invest in carbon abatement, driving the emission level downward.

3.4.2. Effect of parallel instruments on carbon price

We present the mean and median forecasts of the FCPI that were obtained in all simulated scenarios to assess the impact of parallel instruments on the strength of the carbon price signal. Recall from Chapter 2 that the depicted mean FCPI has limited value as a forecast of the actual carbon price because the market price is inherently uncertain and dependent on assumptions regarding the availability and marginal costs of specific technologies.

The forecasted mean FCPIs in 2030 for all scenarios are shown in Figure 3.6. The impact levels of Type 1 and Type 2 instruments (in $MtCO_2$/yr) are shown on the x and y axes respectively, with the mean FCPI shown on the z axis. The Neutral Scenario FCPI level in 2030 is €42 (see also Figure 3.3). The FCPI is responsive to both the introduction of Type 1 and Type 2 instruments. As the combined impact of both types of instruments approaches 30 $MtCO_2$/yr, the mean FCPI approaches zero.

Whereas Figure 3.6 depicts the case for 2030, Figures 3.7 and 3.8 reveal that the FCPI is significantly lower in earlier years as well under the influence of parallel instruments. Two scenarios are depicted in each graph: the Neutral Scenario and a scenario with 20 $MtCO_2$ of abatement via Type 1 (Figure 3.7) or Type 2 (Figure 3.8) instruments.

The medians in Figures 3.7 and 3.8 reveal that the probability distribution of the FCPI becomes positively skewed once parallel instruments are in effect. The medians effectively show that the carbon price is already likely to approach zero if the annual impact of parallel instruments is 20 $MtCO_2$/yr.

When Figures 3.7 and 3.8 are compared with respect to the forecasted carbon price in the 20 $MtCO_2$/yr scenarios, a lower mean FCPI can be seen in the latter figure, indicating that the carbon price is more sensitive to Type 2 instruments over time. The stronger carbon price sensitivity to Type 2 instruments can be explained by burden shifting between ETS and non-ETS sectors. To see why, consider that Type 2 instruments encourage non-ETS firms to pursue investments that reduce emissions in ETS sectors. Type 2 instruments thereby reduce the need for ETS firms to invest in carbon abatement themselves to stay below the emission allowance cap. The reduced pressure on ETS firms is reflected by a lower carbon price, as ETS firms can comply with EU ETS regulation without having to invest in some of the more costly abatement technologies. Type 1 instruments, however, encourage ETS firms to invest in carbon abatement, just as the EU ETS does. Therefore, Type 1 instruments do not shift the abatement burden from ETS sectors to non-ETS sectors. Consequently the carbon price is higher in Figure 3.7 than in Figure 3.8.[19]

3.4.3. Effect of parallel instruments on achieved emission level

In this subsection, we present the mean forecasted emission levels within EU ETS sectors in 2030. Changes to this expected value following the introduction of parallel

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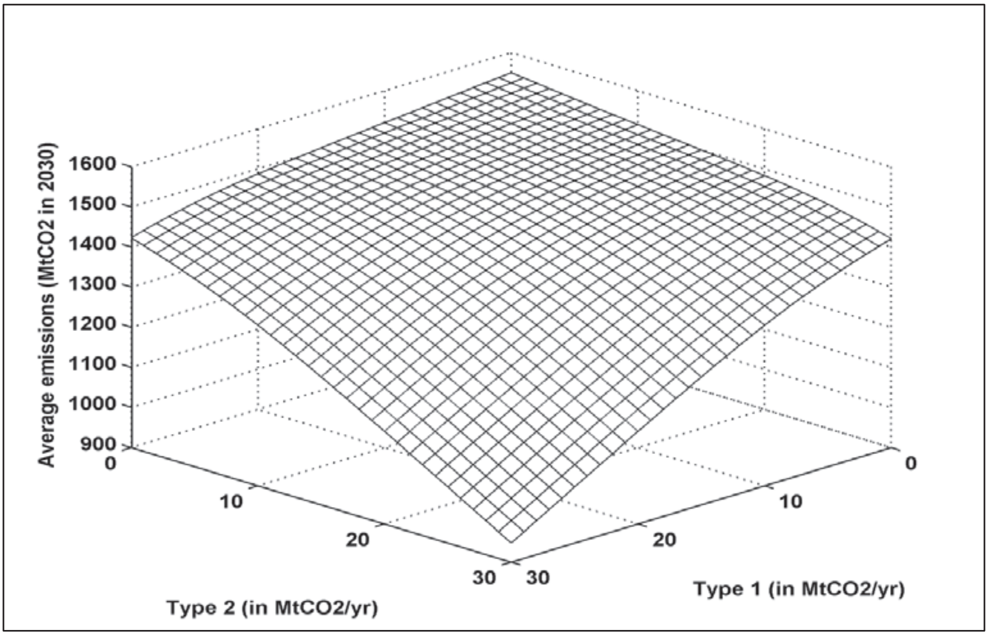
[19] Although Type 1 instruments do not shift the *abatement* burden from ETS firms to non-ETS firms, Type 1 instruments may shift part of the *financial* burden to the government if a Type 1 instrument consists of public financial assistance (*e.g.* subsidies). However, in this study we limit the analysis to the overall effect of parallel instruments on the performance of the EU ETS (notably the carbon price); the financing structure of individual investments is outside the scope of this research.

instruments reveal to what extent Type 1 and Type 2 instruments provide additional emission reduction alongside the EU ETS.

Figure 3.9 shows that a distinction can be made between scenarios with a relatively low impact level of parallel instruments and scenarios with a relatively high impact level of parallel instruments, although the exact threshold level that divides these two classes is hard to determine from Figure 3.9 alone. Whereas the former class of scenarios does not seem to have any significant influence on the emission level, the latter class of scenarios has a strong downward effect on the mean emission level. The two classes of scenarios will be described and discussed separately; the threshold level will be determined and discussed in more detail below.

Note that the emission level attained in the Neutral Scenario is sufficient to comply with EU ETS emission targets. Any emission reduction beyond that level, *e.g.* as a result of

Figure 3.9: Emissions within ETS sectors in 2030



the introduction of parallel instruments, effectively means that governments are overshooting the EU emission target. Pursuing such an abatement strategy seems ill-advised because overshooting the target burdens European economies with unnecessarily high cost, and possible loss of competitiveness. If European policy makers are committed to achieving emission reduction beyond the current target level anyway, lowering the EU ETS allowance cap would be a more straightforward way to achieve that goal.

3.4.3.1. SCENARIOS WITH A RELATIVELY LOW IMPACT OF PARALLEL INSTRUMENTS

If the gross impact via parallel instruments is relatively low, all abatement via parallel instruments is offset via the EU ETS. This occurs because the depreciated carbon price reduces abatement activity in ETS sectors to which the parallel instruments do not apply. For example, Type 1 instruments may speed up abatement activity in the power sector, which relieves the pressure on other ETS sectors (*e.g.* the steel or cement sector) to abate CO_2 and stay below the allowance cap. The net effect is that the emission level remains unchanged.

However, such offset of abatement activity via the EU ETS does not have to occur instantaneously. Parallel instruments typically have opposing effects on the emission level over time. As will be explained below, parallel instruments tend to speed up abatement activity in the short run but to slow it down in the long run. As a result of this intertemporal effect, the forecasted emission level in 2030 can be slightly below the Neutral Scenario level, even if the annual impact is very small. In practice, the small impact on the emission level can be explained by three factors.[20] First, construction lead times regarding abatement technology can delay the response in emissions output, despite an instantaneous response of the carbon price. Second, imperfect information on the emissions trading market could lead to a delayed

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[20] The first two factors are not modeled here; the third factor is accounted for in the simulation and will be discussed in more detail.

Figure 3.10: Abatement and use of banked allowances without parallel instruments in a random year t

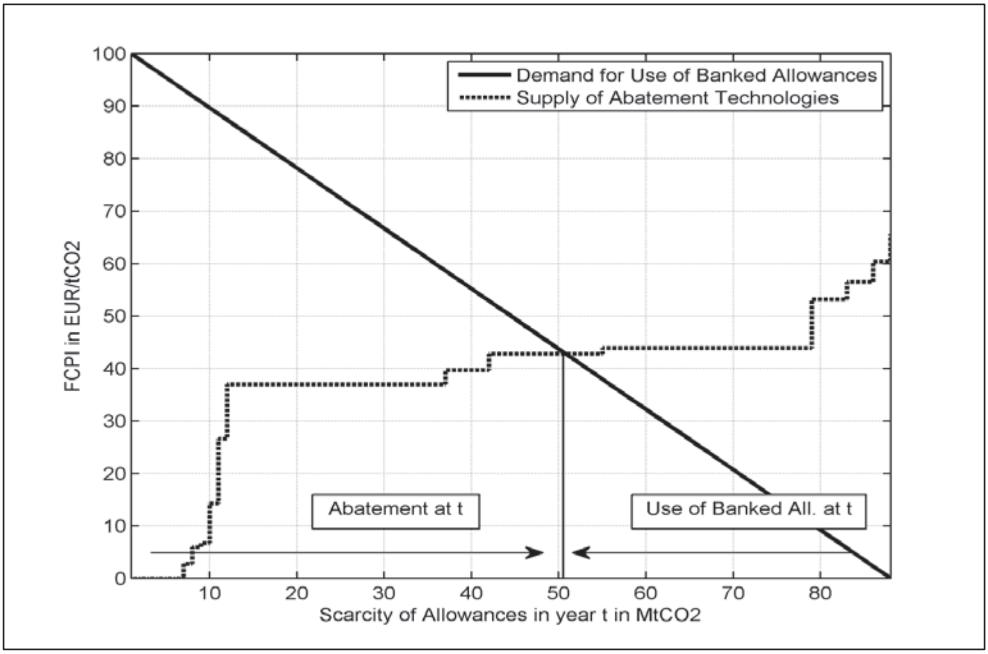
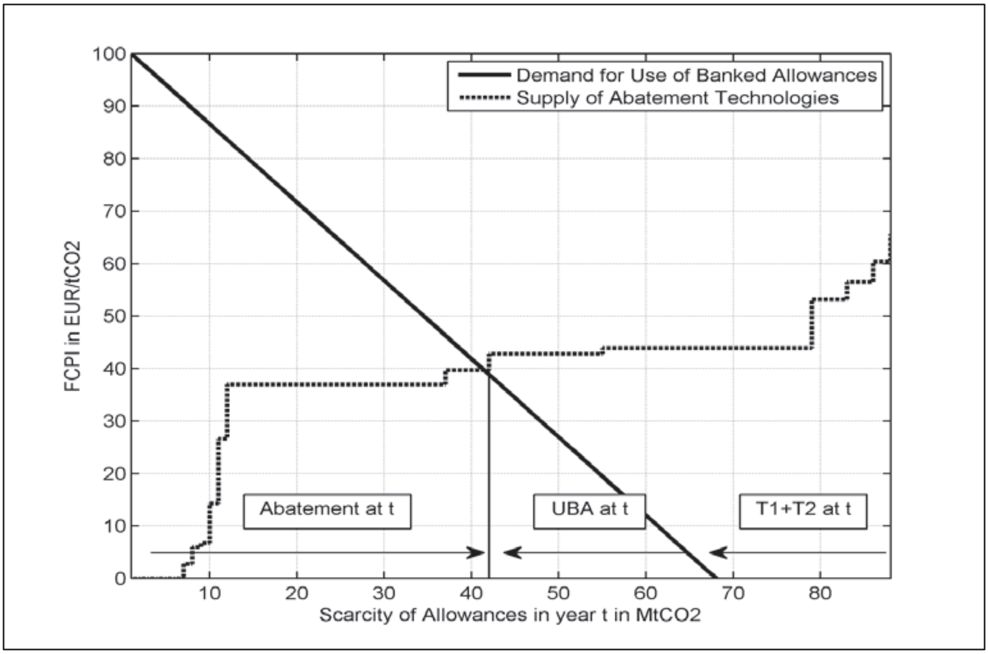


Figure 3.11: Effect of parallel instruments on abatement and use of banked allowances t



downward response of the carbon price. Imperfect information relates to unawareness or the inability of market participants to have full information regarding the future effect of instruments that are introduced by governing bodies across Europe.

A third possible factor relates to the reduced option value of carbon allowances once parallel instruments depreciate the carbon price. To see why, consider the example illustrated in Figures 3.10 and 3.11.

In Figure 3.10, the overall scarcity (88 $MtCO_2$) is divided between abatement (51 $MtCO_2$) and use of banked allowances (37 $MtCO_2$), resulting in a carbon price of €43. Alternatively, if we assume that Type 1 and Type 2 instruments contribute 20 $MtCO_2$ to abatement efforts in that same year (as depicted in Figure 3.11), industries under the EU ETS are not required to use as many banked allowances, or to invest in abatement, to comply with EU ETS regulation.

The carbon price then falls to €40 and abatement activity via the EU ETS is reduced to around 42 $MtCO_2$, while the use of banked allowances is reduced to 26 $MtCO_2$. If we compare the scenarios in Figures 3.10 and 3.11, overall abatement efforts are higher in the latter scenario, as parallel instruments and the EU ETS trigger a total of 62 $MtCO_2$ (42 + 20 $MtCO_2$) whereas only 51 $MtCO_2$ is abated in the former scenario.

The boost in abatement activity in the latter scenario can be attributed to our assumption that firms have unchanged long-term carbon price expectations.[21] Because firms do not lower their long-term carbon price expectations, they have an incentive to hold on to their banked allowances as soon as the carbon price falls. In the end, they anticipate a higher option value in the future. Long-term carbon price expectations may remain unchanged

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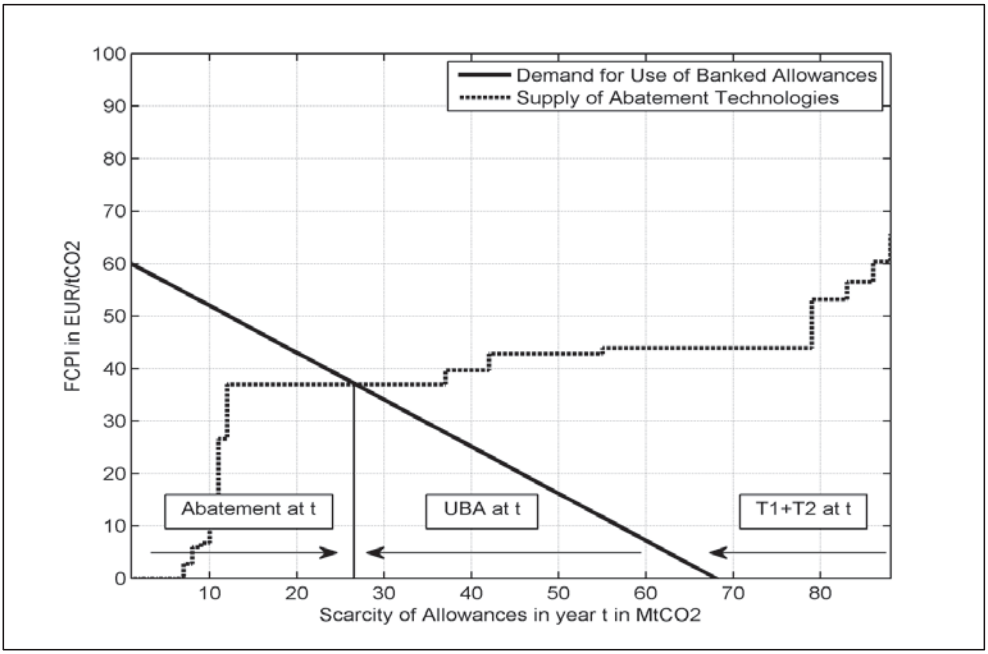
[21] The 'demand for the use of banked allowances' curve still intersects the y-axis at €100 euro per tonne.

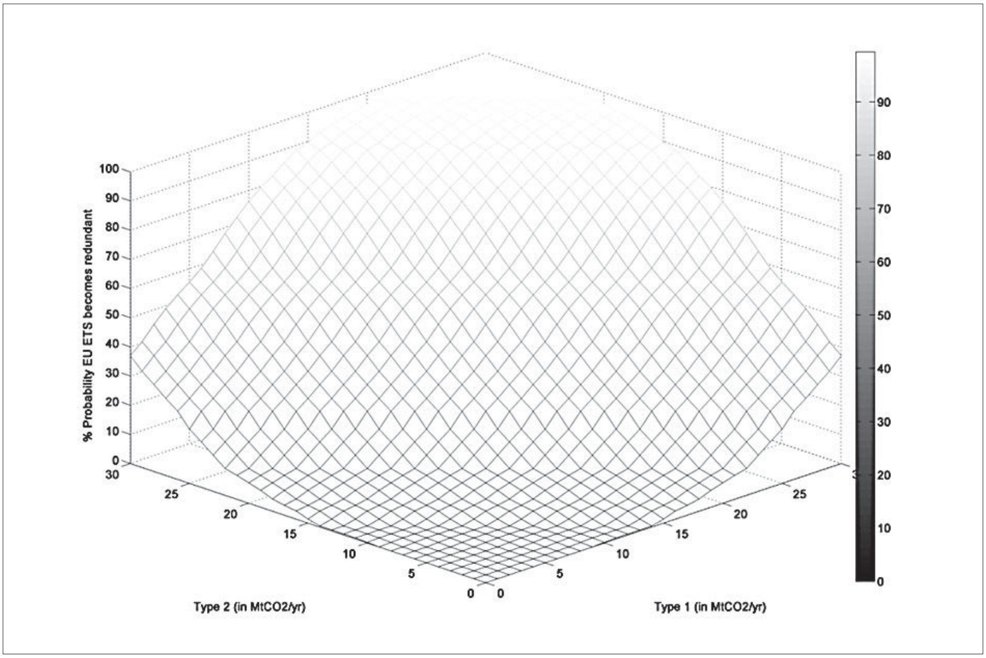
Figure 3.12: Parallel instruments, abatement, and use of banked allowances with lowered carbon price expectations



because firms view parallel instruments as temporary (*e.g.* subsidies), assuming that the EU ETS remains the main instrument of European climate policy in the long term.

If we relax the above assumption, the intertemporal effect on emissions may disappear or even change sign. An example of a scenario with relaxed assumptions is shown in Figure 3.12. Now, the most optimistic firms under the EU ETS anticipate a long-term carbon price of €60 (instead of €100 as in the previous scenarios). As a result, abatement via the EU ETS and parallel instruments totals 46 $MtCO_2$ (–5 $MtCO_2$ relative to the scenario in Figure 3.10) and the use of banked allowances equals 42 $MtCO_2$ (+5 $MtCO_2$). This result indicates that, in addition to a temporary speedup, a temporary slowdown of abatement activity is also possible after the introduction of parallel instruments.

Figure 3.13: Probability that the EU ETS will become redundant



At the extreme, abatement activity via the EU ETS may come to a complete stop if ETS firms decide to dump their banked allowances. Such a scenario would become a possibility if ETS firms were to foresee the possibility of the EU ETS becoming redundant.

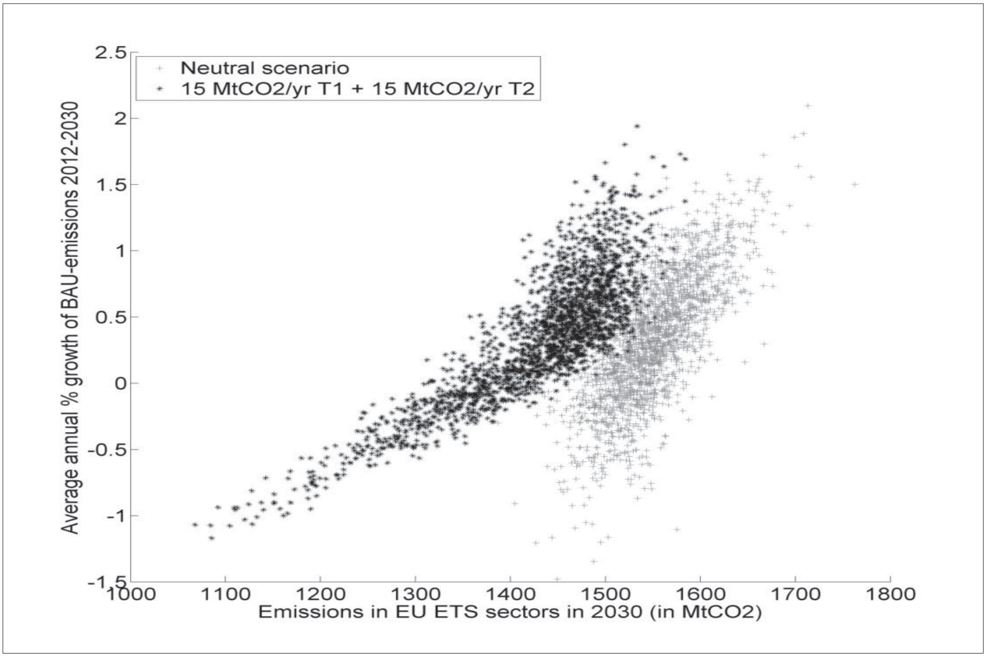
All in all, the scenarios above show that behavioural responses of ETS firms are crucial in determining whether a temporary speedup or slowdown of abatement activity may occur. In practice, it is not well understood how heterogeneous carbon-price expectations and allowance-banking strategies are affected by the introduction of parallel instruments. Nevertheless, the modelling exercise provides insight into possible explanations for a short-term speedup or slowdown in abatement activity. In our modelled scenarios we have assumed that long-term carbon price expectations remain constant. Thus, we have implicitly assumed that firms commit to the EU ETS and anticipate that European policy makers will do the same.

3.4.3.2. SCENARIOS WITH A RELATIVELY HIGH IMPACT OF PARALLEL INSTRUMENTS

In Figure 3.9, the mean emission level decreases steeply if the combined impact of parallel instruments is relatively high. This can be explained by a higher probability that the EU ETS will become redundant. We define EU ETS redundancy as scenarios in which the EU ETS does not trigger any abatement activity. In those scenarios, the carbon price is forced down to zero.

The probability of EU ETS redundancy for each scenario is shown in Figure 3.13. As that figure shows, as long as the annual impact remains below 20 $MtCO_2$, parallel instrument have too little impact to turn the EU ETS into a redundant scheme. If the annual impact of parallel instruments surpasses 20 $MtCO_2$, the EU ETS is in danger of becoming a redundant scheme. If the annual impact rises further, the probability rises steeply. Obviously, once the EU ETS has become a redundant scheme, abatement that is achieved via parallel instruments will no longer be offset via the EU ETS. This explains why in Figure 3.9, the mean forecasted

Figure 3.14: Effect of parallel instruments on forecasted 2030 emission level as a function of the BAU-emissions growth rate



emission level starts to decline if the annual impact of parallel instruments surpasses 20 $MtCO_2$.

Bear in mind that the numbers in Figure 3.9 are mean forecasts. If economic growth were to remain below the historic mean until 2030, less abatement would be required to remain below the EU ETS allowance cap. As a result, the EU ETS would also become redundant more easily. Figure 3.14 illustrates this phenomenon. It shows the forecasted emission level in 2030 as a function of the business-as-usual emissions growth rate between 2012 and 2030 for both the neutral scenario and for a scenario with a total impact by parallel instruments of 30 $MtCO_2$/yr. Regarding the latter scenario, the tail at the lower left shows that the impact of parallel instruments on the forecasted emission level increases significantly if economic growth is below the mean, which signals that the EU ETS has become redundant in these instances. At or above the mean economic growth rates, the forecasted emission level are also somewhat lower, but this can be attributed to a temporary boost in abatement activity and does not necessarily indicate that the EU ETS has become redundant.

The results plotted in Figure 3.13 show that if the combined impact of parallel instruments surpasses 45 $MtCO_2$ per annum, the EU ETS will undoubtedly become redundant. If the combined impact is in between 20 and 45 $MtCO_2$ per annum, the future of the EU ETS is uncertain and hinges on economic growth rates in Europe.

The above threshold levels can be considered high estimates for two reasons. First, redundancy is defined rather strictly (zero abatement via the EU ETS). Even if a small amount of abatement is triggered by the EU ETS until 2030, reflected by a positive albeit low carbon price, policy makers are unlikely to remain as supportive of the EU ETS as they are today. The examples in Figures 3.7 and 3.8 show that the carbon price is likely to be weak even if the combined impact of parallel instruments is just 20 $MtCO_{2.}$ Second, in all scenarios, the long-term carbon price expectations by firms are assumed to be unaffected by parallel instruments. Thus, we assume that firms commit to the EU ETS unconditionally, and do not anticipate its redundancy. Yet, in practice, firms could lose faith in the future of the EU ETS and dump their stock of banked allowances. All in all, if policy makers and firms take positions that further undermine the strength of the scheme, the actual threshold levels for redundancy may lie significantly below the levels that we have established.

3.5. Discussion

The results presented above reveal that the role of the EU ETS can be severely weakened as the aggregate impact of parallel instruments gets to levels in the order of 20 $MtCO_2$/yr. Note that 20 $MtCO_2$ is equal to only a 1 percent reduction of annual emissions under the EU ETS. To compare, the EU ETS allowance cap is currently reduced by 1.74 percent per annum, and set to become 2.2 percent starting in 2021 (EC, 2014b). Thus, even if the impact of parallel instruments were to be far below the intended reduction of the emissions cap, the EU ETS could be weakened to the extent that redundancy could become a real option, especially if some firms or policy makers were to lose their commitment to the scheme.

The factor that explains this phenomenon is the uncertainty of future economic growth and allowance demand: if economic growth stagnates, the chances of EU ETS redundancy increase sharply.

In previous studies of the redundancy of an ETS, stochastic demand patterns were not incorporated in the analysis. Also, the aggregate impact of multiple parallel instruments, as opposed to just one or two instruments, was largely overlooked. Especially the combination of these two factors, however, seems to put the effectiveness of an emissions trading scheme in a less optimistic perspective.

The threshold levels that were determined here offer European policy makers further tools for evaluating and controlling EU ETS performance. Rather than banning the use of parallel instruments, EU member states could introduce a cap on the use of parallel instruments based on these threshold levels. That is, a cap (in $MtCO_2$ of abatement achieved per annum) could be set on the maximum allowed use of parallel instruments in each member state. In that manner, the total impact of parallel instruments could remain well below the threshold level. Although its implementation is unlikely to be an easy exercise, a ‘cap on parallel instruments’ would have two advantages. First, it would ensure that the economic and competitive advantages of cooperation via the EU ETS would be reaped, as (possibly unintentional) lower effectiveness of even redundancy of the EU ETS would be avoided. Second, the cap would stimulate national governments to introduce only those parallel instruments that would offer the greatest local benefits. In that manner, local governments would be forced to allocate public resources in a more cost-efficient manner, and would make them aware of adverse interactions between the EU ETS and parallel instruments.

It would be valuable to examine whether a cap on parallel instruments is compatible with a policy setting with multiple energy and climate targets. More specifically, if the use of parallel instruments were to be restricted, stringent renewables and energy efficiency targets might become unachievable. It also could imply that policy makers would first have to lower the EU ETS allowance cap before allowing for a higher cap on the use of parallel instruments. Alternatively, policy makers could set less ambitious national renewables and energy efficiency targets. In either case, a cap on parallel instruments would give policy makers an incentive to design a more coherent policy setting in which adverse interactions would be reduced to a minimum and public resources would be used in a cost-efficient manner. In the process, also a loss of control could be avoided.

As long as a cap on the use of parallel instruments is not in place, the results suggest that policy makers should be careful with the introduction of parallel instruments alongside the EU ETS if the scheme is intended to play an important role as an incentive for the deployment of CO_2 abatement technologies. Aggressively passing and implementing non-EU ETS instruments while carbon prices are already low could moreover block an upward trend in the carbon price and ultimately lead to the redundancy of the EU ETS.

3.6. Conclusion

The results show that if the aggregate abatement impact of parallel instruments alongside the EU ETS is below approximately 20 $MtCO_2$/yr, the forecasted mean emission level remains unaffected. This occurs because all abatement via parallel instruments is offset via the EU ETS.

The forecasted emission level does decrease significantly if the aggregate impact of parallel instruments surpasses the level of 20 $MtCO_2$/yr. This can be explained by a greater probability that the EU ETS will become redundant, *i.e.* if the scheme fails to trigger any abatement between 2013 and 2030. If the combined impact of parallel instruments is in between 20 and 45 $MtCO_2$/yr, the future real impact of the EU ETS is uncertain, and hinges on the overall economic growth rates in Europe. The lower the average rate of economic growth, the greater the likelihood that the EU ETS becomes redundant. The model results suggest that redundancy of the EU ETS is certain if the combined impact of parallel instruments surpasses 45 $MtCO_2$ per annum. We have multiple reasons to believe that in reality these estimates are conservative, and that the actual threshold levels could be below the reported figures.

When differentiating between types of parallel instruments, the results show that Type 2 instruments lead to a stronger depreciation of the EU ETS carbon price than Type 1 instruments. This can be explained by the fact that the former type of instruments lead to burden shifting between sectors: investments by end-use sectors effectively reduce the need for ETS sectors to invest in carbon abatement. If policymakers prioritize a strong EU ETS performance, the results suggest that they should be restrictive in introducing parallel instruments in both ETS and non-ETS sectors if the carbon price is already weak.

4. THE EU ETS IN THE POLICY MIX: MEASURING THE IMPACT OF INSTRUMENTS IN THE GERMAN POWER SECTOR ON THE PERFORMANCE OF THE EU ETS

4.1. Introduction

In 2005, EU member-states chose for the European Union Emissions Trading Scheme (EU ETS) as a collective means to reduce CO_2 emissions in energy intensive sectors. Meanwhile, individual member-states also govern a wide array of domestic instruments in parallel to the EU ETS. These parallel instruments are generally intended to further stimulate CO_2 reduction efforts domestically. However, if parallel instruments are introduced by an EU member-state alongside the EU ETS, their net effect on the EU emission level will often be zero, compared to a scenario with just the EU ETS (Interact, 2003; Harrison *et al.*, 2005; Sorrell *et al.*, 2009). A parallel instrument may stimulate CO_2 abatement efforts in the member-state where it is introduced. However, in that case it simultaneously provides downward pressure on the EU ETS carbon price because the demand for carbon allowances falls. In response to the lower carbon price, other EU member-stated are inclined to emit more CO_2, leaving the overall emission level unchanged (Interact, 2003; Harrison *et al.*, 2005; Sorrell *et al.*, 2009). In its extreme, parallel instruments could drive the EU ETS carbon price to zero euros permanently, signalling a de facto end to international cooperation regarding CO_2 abatement in Europe. Given the key role that was assigned by policymakers to the EU ETS in 2005, the simultaneous introduction of a range of parallel instruments that leave the emission level unchanged but potentially obstruct the functioning of the EU ETS seems counter intuitive. Consequently, policymakers need a thorough understanding of the magnitude of such interaction effects between parallel instruments and the EU ETS in order to be able to design a policy mix that is coherent with their policy objectives.

Despite a lower than expected EU ETS carbon price since 2005, the role of parallel instruments as an explanation for recent low carbon prices remains unclear. Although many papers have identified the existence of a negative relationship between the number of parallel instruments and a market-based carbon price (*e.g.* Hindsberger *et al.*, 2003; Böhringer *et al.*, 2009; Böhringer and Rosendahl, 2010; Linares *et al.*, 2008; Morris *et al.*, 2010), few have quantified the impact of parallel instruments on the current performance of the EU ETS. The low EU ETS carbon price is typically attributed to the over allocation of emission rights, and below average economic growth (Siikamäki *et al.*, 2012), while the role of parallel instruments remains unclear. In Chapter 3 of this study we did find two key thresholds levels regarding the sensitivity of the EU ETS to parallel instruments: (1) if parallel instruments trigger more abatement than 45 $MtCO_2$ per year, the EU ETS carbon price is certain to fall to zero euros. Thereby, international cooperation via the scheme would come to a halt; (2) if the impact of parallel instruments falls below 20 $MtCO_2$ per year, the EU ETS is able to co-exist with parallel instruments, although a significantly depreciated carbon price is likely if the annual impact approaches 20 $MtCO_2$ per year. If the aggregate impact of parallel instruments falls in between 20 and 45 $MtCO_2$ per year, the role of the EU ETS is uncertain and depends on future economic growth rates around Europe.

Building on these thresholds, we need a forecast of the impact of the parallel instruments on CO_2 abatement activity in EU member-states to determine the future role of the EU ETS in the policy mix. In this chapter, we aim to estimate that impact so that European and domestic policymakers can assess whether the current mix of instruments is expected to match their long-term policy goals. If policymakers prioritize the creation of a level-playing-field through an EU-wide carbon price, the results of such a study could suggest that policymakers should rely less on parallel instruments because their combined impact could or will ultimately lead to the redundancy of the EU ETS.

In this study, we determine the impact on abatement activity of two key parallel instruments that have been introduced in the German power sector. Namely, Feed-In Tariffs

(FITs) and the Nuclear Phase Out (NPO). FITs are fixed tariffs that are paid to owners of newly built renewable sources of electricity. The level of the tariff is technology specific, depending on the cost of electricity generation. For example, solar power is awarded a higher tariff than wind power. The level of the tariff is fixed in long-term contracts and is awarded for each kilowatt hour of electricity that is produced. The NPO refers to the timetable that was set up by the German government to decommission all nuclear generation capacity before the end of 2022. Note that the NPO is primarily an energy policy measure and not specifically a CO_2 abatement measure. However, through its impact on the electricity generation mix, the NPO is likely to seriously impact the CO_2 emission level. Because nuclear electricity generation has a relatively low CO_2 intensity, the NPO is likely to lead to an increase in the CO_2 emission level of the German electricity sector as nuclear power will be replaced by technologies that, on average, have a higher CO_2 intensity.

We choose to focus on the German power sector for three reasons. First, the German power sector is the largest sector within the EU ETS, covering about 15% of all emissions under the EU ETS. Policies aimed at this sector are therefore most likely to have a significant impact on the performance of the EU ETS. Second, the German government has put in to place a relatively ambitious domestic agenda for the power sector, as it aims for increased use of renewable electricity supply, CO_2 abatement and a nuclear power. This agenda is matched by a set of instruments that are likely to have a significant effect on the CO_2 emission level in the German power sector. Finally, it is impossible to model all parallel instruments that interact with the EU ETS across Europe in a detailed manner given the wide array of instruments, countries and sectors that should be included in such an analysis. Nevertheless, apart from the two German parallel instruments we have modelled explicitly, we do account for the influence of other parallel instruments in a stylized manner in Section 4.4.4. In that section, we examine the abatement impact of parallel instruments in the German power sector while broadly representing the prevalence of parallel instruments in other sectors and countries across the EU. How parallel instruments in other sectors and countries are modelled specifically is detailed in Section 4.4.4.

To perform the required analysis, a model is needed that captures both the impact of instruments on the level of CO_2 emissions in the German power sector, as well as the expected interaction effects between the EU ETS and parallel instruments. The latter element is often lacking in existing analyses because the strength of the CO_2 price incentive is determined exogenously (Weigt *et al.*, 2012). As a result, possible interaction effects between the instruments, which have been extensively documented in previous literature (Hindsberger *et al.*, 2003; Linares *et al.*, 2008; Böhringer *et al.*, 2009; Böhringer and Rosendahl, 2010; Morris *et al.*, 2010), are omitted. Therefore, to examine the impact of parallel instruments on the expected emission level and carbon price, a more realistic representation of an ETS with an endogenously determined carbon price would be required.

In this study, we apply a stochastic simulation model to capture the interactions between domestic instruments, the EU ETS, and the German power sector between 2008 and 2030 (see Figure 4.1 in Section 4.3.1 for a model overview). The model works on a relatively high level of aggregation, but is used to model interactions between social, economic and technological systems. For example, we do not model the electricity production level at a plant level, but aggregate production levels for each technology type. Thereby, we assume that all plants of a particular technology type have the same technological and financial characteristics.

We capture key dynamic – and interacting - factors that are expected to have a profound impact on the emission level and carbon price by modelling stochastics in a relatively straight-forward way. Specifically, the economic growth rate, fuel prices, solar irradiance levels and wind speeds are modelled stochastically.[22] The uncertain stochastic nature of each of these variables has a significant effect on operational and investment decisions of operators in the power sector and thereby affects the emission level and carbon price. The level of economic growth determines the need for, and profitability of, investments in generation capacity (Crousillat, 1989; Moreira *et al.*, 2004; Vithayasrichareon and MacGill, 2012). The economic growth rate thereby affects the expected long-term composition of the electricity generation mix. As the composition of the generation mix changes, naturally its CO_2 emission output will change as well. The stochastic nature of fuel prices drives both the profitability of investments in specific generation technologies (Crousillat, 1989; Krey *et al.*, 2007; Mirkhani and Saboohi, 2012; Vithayasrichareon and MacGill, 2012) as well as fuel switching behaviour between existing gas, oil and coal-fired power plants (Söderholm, 2000, 2001; Krey *et al.*, 2007). Because gas-fired power plants have a significantly lower carbon intensity compared to oil and coal-fired plants, fuel price uncertainty can also significantly affect the emission level and carbon price (Chevallier, 2009). In turn, uncertain solar intensities and wind speed levels drive the availability of renewable, low-carbon, sources of supply (Lun and Lam, 2000; Hetzer *et al.*, 2008). For example, in Germany, the difference between a year with high solar irradiance levels (95th percentile) and a year with low solar irradiance levels (5th percentile) in Germany translates into roughly a 16% difference of the annual electricity output of solar-based technologies (Šúri *et al.*, 2007). The intermittent nature of solar and wind power also implies that the capacity utilization, emission output and

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[22] Radical technological innovation could also be modelled as an exogenous stochastic process (Silverberg and Verspagen, 2003), but is not explicitly covered in this study. In the sensitivity analysis, we do *explicitly* account for innovation via experience curve effects. Experience curve effects can also be approximated as an exogenous stochastic process (Grubb *et al.*, 2002; Papineau, 2006). However, we model this type of innovation as an endogenous process that is dependent on the rate of deployment of a technology. In that manner, we stick closely to the core principle behind experience curve effects, in the sense that cost reductions are directly related to experience that is gained with a technology (Junginger *et al.*, 2010).

profitability of thermal power plants is affected as they have to adjust to the unpredictable supply of renewable electricity (GE Electric, 2010; Hart and Jacobsen, 2011; *Hart et al., 2012*). Obviously, the impact of intermittent technologies on operational and investment decisions depends critically on their penetration level.

As opposed to a deterministic approach, the stochastic approach ensures that we do not make implicit technological choices based on the aforementioned variables. Also, the confidence intervals around output parameters allow us to assess the likelihood of scenario outcomes. Because each of the stochastic parameters influences the emission level, they also interact with the strength of the EU ETS carbon price incentive. Higher emission levels provide upward pressure for the carbon price, stimulating investments in technologies with a low CO_2-intensity. Alternatively, low emission levels provide downward pressure on the CO_2-price, and slow down the rate of investments in technologies with a low CO_2-intensity. By running the model for a range of policy scenarios, the impact of individual policy instruments on the emission level can be simulated.

We find that the combined impact of FITs and the NPO leaves the overall emission level in Europe unchanged, yet depreciates the EU ETS carbon price with an average of 15%. Given that all 30 countries under the EU ETS govern a much wider range of parallel instruments, not limited to the two under study here, the results suggest that parallel instruments are a prominent driver behind the relatively low carbon prices that are witnessed in the market today. EU member states that are most ambitious with introducing parallel instruments carry the most of the burden to abate CO_2 in Europe while member states that do nothing are, at least partly, left off the hook. We proceed with a concise description of the literature on the interaction between instruments and targets in Section 4.2. The methodology follows in Section 4.3. The results and sensitivity analysis are covered in Section 4.4. Finally, the discussion and conclusion follow in sections 4.5 and 4.6.

4.2. Theory on interacting targets and instruments

4.2.1. Controllability of a policy mix

The assignment of interacting policy instruments to targets is known as the assignment problem and has its roots in the work of Tinbergen (1952; 1956). Tinbergen formulated general rules for the controllability of a policy mix. He coined the rule that the number of independent instruments must equal the number of independent targets for a solution to exist. The term solution refers to the ability to reach all policy targets. Whereas Tinbergen coined the rule for *existence* of a solution, Mundell (1962) formulated a key principle for *attainment* of that solution with regard to monetary and fiscal policy targets. Mundell's Principle of Effective Market Classification states that an instrument should be paired with the target on which it has the greatest comparative influence. Specifically, he calculated that fiscal instruments should be used to attain internal macro-economic stability (relating to inflation and economic growth targets) and that monetary instruments should be used to attain external macro-economic stability (relating to balance of payments and exchange rate targets). He demonstrated that failure to do so (*e.g.* by using fiscal instruments to achieve external macro-economic stability) would bring policymakers further out of course with their policy targets. These fundamental principles underline that policymakers should carefully select, design and assign instruments to policy targets in order to be able to achieve their target. Without a careful configuration of the policy mix achieving policy targets can become impossible or simply be the result of good fortune.

In this study, we analyse a policy mix with more instruments than targets. The EU CO_2 emission-reduction target is pursued with multiple instruments that are governed by multiple relatively autonomous governments (the EU, as well as 31 individual states[23]). A policy mix with more instruments than targets has many possible solutions[24] (Tinbergen, 1952; Di Bartolomeo *et al.*, 2011; Acocella *et al.*, 2012). However, such a solution can be hard, if not impossible, to obtain in practice it requires strong coordination by a central planner. That planner should set all excess instruments at arbitrary fixed values, while having full information regarding the relations between instruments, targets and the behaviour of the private sector. Without a social planner or full information, a solution becomes indeterminate and uncontrollable for all governments involved (Di Bartolomeo *et al.*, 2011; Acocella *et al.*, 2012). We study a policy mix that is neither governed by a central planner, nor can its future impact on the economic system be estimated with full certainty. Among other, uncertainty regarding fuel prices, economic growth rates and investment behaviour by the private sector imply that it is impossible for policymakers to calibrate all instruments such that a set of predefined fixed targets is met with certainty. Given this configuration, some loss of control over policy outcomes is inescapable. If instruments cannot be assigned to a target in a manner that guarantees that the goal is achieved, the objective becomes to maximize the likelihood that targets are met, or to minimize the likelihood of unwanted outcomes. The model that is developed in this study is a step towards that objective because our stochastic approach allows us to assess the likelihood of policy outcomes.

Despite a possible loss of control, policymakers may opt for a complex mix of instruments for a variety of reasons. Pizer (2002) points out that the use of multiple

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[23] The EU consists out of 28 member states, but Norway and Liechtenstein and Iceland also participate in the EU ETS.

[24] Tinbergen (1952) notes that in an overdetermined system there is always one among the infinity of available solutions that maximizes welfare. If policymakers pursue fixed targets, as opposed to maximum welfare, the “problem” of “too many instruments” is introduced.

instruments may increase the credibility of a certain policy objective. He argues that a combination of instruments increases the number of tools that are available to policymakers, thereby strengthening their ability to respond to a crisis. Actors in the private sector know that the government is able to intervene in the event of a crisis and therefore see the policy objective and instrument as more credible. Sorrell and Sijm (2003) argue that combinations of instruments can be useful in relation to emission trading if it leads to an improvement of the static or dynamic efficiency of a trading scheme or if it delivers other valuable policy objectives. Bennear and Stavins (2007) note that multiple instruments can be justified in case of multiple market failures or if an exogenous constraint cannot be removed. We note that, although the mentioned benefits could exist, they should always be weighed against the cost of adverse interaction effects. Obtaining a reliable quantitative estimate of such costs and benefits is challenging but also important for anyone that is interested in designing a policy mix that is congruent to policy objectives.

4.2.2. Policy congestion in the environmental domain

Glachant (2001) studied whether the outcomes of environmental EU Directives[25] were in line with the targets. He found that this is rarely the case and cited that interaction with other legislation (including non-environmental legislation) on the EU or nation state level was the primary cause for either non- or over-compliance with EU directives. He called for an adaptive design of policy instruments so that its configuration can be altered at a low cost when circumstances change.

Interact (2003) was one of the first large research projects on policy interactions regarding climate policy. The project was funded by the European Commission to identify

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[25] He studied Directive 89/429 regulating atmospheric emission from domestic waste incinerators, Directive 88/609 dealing with SO_2 and NO_X emissions from large combustion plants and the Council Regulation 1836/93 concerning the voluntary participation of industrial companies in an EU Eco-management and Audit scheme (EMAS).

potentially hazardous interactions (between the EU ETS and parallel instruments) and thereby inform policymakers across the EU. The project's final report presents an extensive typology regarding interaction types and effects and has resulted in a number of academic publications that warn for adverse interaction effects (Smith and Sorrell, 2001; Boemare and Quirion, 2002; Mavrakis and Konidari, 2002; Boemare *et al.*, 2003; Sorrell and Sijm, 2003). Adverse interaction effects that were identified include double counting problems (where avoided emissions are rewarded twice, emissions are penalised twice, or even penalized and rewarded at the same time via different instruments), a reduced allocative efficiency of the EU ETS (see also Sinn (2011)) and a lower carbon price (see also Frankhauser *et al.* (2010) and Hindsberger *et al.* (2003)). However, the warnings for adverse interactions are accompanied by at least as much rationales for co-existence of emission trading schemes with parallel instruments. Rationales for the use of parallel instruments that were identified by Interact (2003) include the need to overcome market failures that block technological innovation (see also Jaffe *et al.* (2005) and Oikonomou (2010)), mitigating allowance price uncertainty and capturing windfall profits[26]. Market failures can come in the form of imperfect information on energy efficiency opportunities. Instruments that correct such market failures may increase the dynamic and static efficiency of an emissions trading scheme. In turn, instruments that reduce carbon price uncertainty (*e.g.* by implementing a carbon price ceiling and floor (Pizer, 1999; Mckibbin and Wilcoxen, 2002)) or capture windfall profits (*e.g.* by auctioning allowances instead of choosing for free allocation (Woerdman *et al.*, 2009)) could improve the political acceptability of an emissions trading scheme.

A number of studies followed in subsequent years, especially concerning interaction effects between emission trading schemes and renewable support schemes. Del Rio (2007)

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[26] Here, windfall profits relate to the 'free money' that is received by firms under the EU ETS when emission allowances are distributed for free, while these allowances have a positive monetary value via the ETS exchange.

performed a literature review on these studies, although he concludes that it remains an under-researched field. Also he concludes that results are often context-specific and/or based on simple numerical examples with arbitrary numbers. Del Rio thus calls for more rigorous empirical research in settings that closely approach the conditions in real-world markets.

Based on the groundwork of the Interact project and subsequent literature on the topic, Oikonomou and Jepma (2008) developed a qualitative analytical framework that combines all of the identified (beneficial or adverse) interactions. The framework can be used to generate an overview of the interactions that are to be anticipated in a policy mix. The analytical framework can be applied to any set of climate instruments that is under consideration. An important limitation of the framework is that it leaves the important task of determining the strength of an interaction as well as the relative weight of that interaction to the user of the framework. In absence of accurate data on the interaction effects, any policy mix could be justified depending on expert views.

Despite increasing attention to the topic of policy interaction, Bye and Bruvoll (2008) state that policy development in the energy and environmental domain has already resulted into an overly congested policy space. They conclude that very little empirical evidence is available about the aggregate effect of environmental instruments. Bye and Bruvoll call for coordination and simplification of policy tools before new and primarily equivalent instruments are added to the policy space.

Recently, the Appraise research project (Apraise, 2014) presented the 3E method. The qualitative 3E method is an iterative series of analytical steps to, first, identify interaction effects between environmental instruments and, secondly, use this information to build a policy mix that is (more) robust against unwanted interactions. One of the 12 case studies that were performed with the 3E method focussed on the attainability of hydropower deployment targets in Austria. The study found that EU legislation on bio-diversity and water quality potentially leads to non-compliance regarding EU legislation on renewables targets. In absence of guidelines to balance the needs for renewables, bio-diversity and water quality, the current policy setting is likely to be set up for failure regarding at least one of the environmental targets.

The authors stress that, although the Apraise 3E method is qualitative, it can also be used to improve the internal coherence of scenarios that are used in quantitative forecast models. Although we do employ a quantitative forecasting model in this study, we did not apply the 3E method in the design process. We suggest that the 3E method is particularly useful if it would become a routine procedure for policymakers to create awareness of interaction effects while designing a policy instrument. Given that awareness of interaction effects was both the starting and focal point of our research, a direct application of the 3E method had no added value here. That does not mean that our model covers the all of the interaction effect that may be anticipated within the policy space of the EU ETS.[27] As mentioned in the introduction, for practical purposes we limit ourselves to the interaction effects between the EU ETS and key instruments in the German power sector.

Along the lines of the suggestion made by Del Rio (2007), we aim to provide a detailed case study that closely approaches the conditions in the real world. In that manner, our results may provide a better insight and be of greater relevance to policymakers, than previous theoretical studies that were based on more simplistic models and assumptions. Greater relevance and applicability of modelling results may help policymakers to weigh more accurately the potential adverse and beneficial interaction effects, for example when

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[27] For example, the German government also has a Special Energy and Climate Fund (Esch, 2013) with which, among other, renewable electricity and energy efficiency projects are financed. This fund may interact in a similar manner with the EU ETS as the FITs do. However, the program is significantly smaller in size and is therefore left out of this analysis.

applying the analytical framework that was developed by Oikonomou and Jepma (2008) or the 3E method (Apraise, 2014).

4.2.3. Quantitative Modelling of EU ETS with German FITs and NPO

In this section we provide a concise overview of key quantitative modelling attempts regarding the interaction effects between the EU ETS, FITs and/or the NPO.

Rathmann (2007) analysed the electricity price effects of introducing FITs in Germany alongside the EU ETS. He showed that electricity prices are expected to fall as long as the slope of the abatement cost curve[28] lies above a threshold level of 0.16 (€/tCO_2)/(MtCO_2/yr). Rathmann estimates the slope of the abatement cost curve by dividing the CO_2-price under the EU ETS in 2005 (€20/tCO_2) with the expected short position of the EU ETS (70 MtCO_2/yr). The slope of the marginal abatement cost curve was estimated to be 0.29 (€/tCO_2)/(MtCO_2/yr), which lies above the threshold level of 0.16 (€/t)/(Mt/yr) leading to the conclusion that electricity prices are likely to fall. Also, with a rough estimation, he argued that, in absence of European targets for renewable electricity deployment, the EU ETS carbon price should have been approximately €53 instead of around €20 in 2005. In other words, these results suggest that introduction of targets for renewable electricity around Europe leads to a carbon price depreciation of more than 60%. The author does note that this estimate is very rough because of the highly stylized analytical model. In particular, Rathmann (2007) lacked detailed information regarding the actual shape of the marginal abatement cost curve around Europe and used static information regarding the carbon price and expected short

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[28] FITs are financed via a mark-up on the retail electricity price and thereby put upward pressure on the electricity price. At the same time, FITs are a substitute for an ETS and thus also put downward pressure on the CO_2 price (and thereby downward pressure on the electricity price). The greater the slope of the abatement cost curve, the greater the latter effect.

position of the EU ETS in 2005 to infer its slope.[29] As a result, he notes that the carbon price dynamics that are to be expected remain unclear and call for further research. Rathmann's rough estimate did show that the sensitivity of the EU ETS carbon price to the introduction of parallel instruments may be rather strong.

In our model, the EU ETS carbon price and short position are simulated dynamically over time, reflecting the fact that neither is necessarily linear or constant over time.[30] Based on a detailed account of the expected abatement costs across the EU, stochastic emission growth rates and explicit modelling of allowance banking behaviour by participants under the EU ETS, we are able to model the interaction effects between the EU ETS carbon price and German FITs with a greater level of precision that Rathmann (2007).

Abrell and Weight (2008) analysed how the EU ETS and German FITs interact using a computable general equilibrium (CGE) model with data from 2004 on the German economy. They conclude that in the extreme, FITs can lead to an excess of carbon allowances and a zero euro carbon price. However, the limited scope of the analysis (Germany only), the outdated data from 2004 and the static and simplistic manner in which emissions trading is represented (as a non-tradable emissions quota) imply that these results have little value with regard to the performance of the actual EU ETS or the German FITs. The fact that stringent targets for renewable deployment can make the EU ETS redundant, with a carbon price of zero euro, has also been demonstrated analytically in different settings by De Jonghe *et al.* (2009) and Hindsberger *et al.* (2003). All of these papers show that a zero euro carbon price is theoretically possible yet do not show whether it is a probable outcome.

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[29] The short position of the EU ETS refers to the scarcity of allowances. The scarcity of allowances under the EU ETS is uncertain and unstable over time. As a result, relying on an ex-ante static forecast to estimate the short position of the EU ETS can lead to inaccurate modelling results.

[30] For example, fuel price fluctuations affect the marginal cost of CO_2 abatement, and thereby the shape of the abatement cost curve. Economic growth fluctuations and allowance banking behaviour affect the short position under the EU ETS.

Because of the probabilistic approach in this study, we are able to evaluate the likelihood of an outcome. For example, we will be able to demonstrate whether it is likely that the FITs and NPO lead to redundancy of the EU ETS. Probability distributions of the CO_2 price and emissions level will be provided in the results section for each scenario that we test.

Traber and Kemfert (2009) performed an ex-post analysis of the impact of FITs on the emission level and electricity price in Germany. Based on 2006 data, they find that the introduction of FITs changed the emission level by -11%. In their analysis they distinguish between a substitution effect (-16%) and a permit price effect (+5%). The substitution effect entails that, if FITs are introduced, production switches from conventional production capacity to renewable low-carbon production capacity. The permit price effect covers the fact that the carbon price falls after the introduction of FITs leading to a stimulus for carbon intensive production capacity. They note that the overall emission level in Europe as a whole remains unchanged.

Traber and Kemfert (2009) also estimate that the introduction of FITs lead to a fall of the 2006 carbon price from 23 to 20 euro per allowance (-15%). Interestingly, they do not find evidence for the theoretically possible decrease in consumer electricity prices, as documented by Rathmann (2007). Instead, Traber and Kemfert (2009) identify a pronounced increase in the consumer electricity prices. This can be explained by the fact that large conventional producers exhibit some level of market power and are able to shift the burden of the FIT (the cost incurred due to lower production rates of conventional plants) from producers to consumers (via a higher electricity price).

In a working paper, Traber and Kemfert (2012) also analyse the impact of the NPO on the EU ETS carbon price. They find an increase of the carbon price between 1.8 and 2.6 euro per allowance by 2020 under the current EU ETS regime. This is in line with the 2 euro jump of the EU ETS carbon price when the NPO was publicly announced in March 2011 (Matthes *et al.*, 2011).

Traber and Kemfert (2009, 2012) employ a model that covers the electricity sector in 25 EU countries. Albeit static, their representation of the electricity sectors across the EU is more detailed than the models used by Rathmann (2007), Abrell and Weigt (2008) and the model in this study. However, the static nature of the model implies that the EU ETS is also represented in a simple and static manner by Traber and Kemfert (2009); a critique that can also applicable to Rathmann (2007) and Abrell and Weigt (2008). The static EU ETS metrics from 2005 (Rathmann, 2007) and 2006 (Traber and Kemfert, 2009) that were used in the analyses do not accurately represent the form and functioning of the EU ETS since the start of Phase II of the EU ETS in 2008. Among others, the ETS allowance supply regime has been strongly adjusted at the start of Phase II. Also, banking of allowances became a possibility for firms under the scheme in 2008.

Because firms are allowed to bank allowances (and can thereby offset a short position in one year with surpluses from previous years), we stress that models of emission trading schemes should account for the cumulative supply and demand of allowances over an extended period of time to accurately assess the need for CO_2 abatement, and the level of the carbon price. For example, the financial crisis in 2008 and subsequent economic crisis showed how vulnerable the performance of the EU ETS is to allowance demand uncertainty. The fall in economic output resulted in a large surplus of carbon allowances that rendered abatement activity unnecessary for years to come while also supressing the carbon price (see Section 2.3). Parallel instruments could therefore have a stronger or weaker effect on the EU ETS carbon price, depending on the availability of banked allowances, the prevailing level of economic growth and the slope of the marginal abatement cost curve.

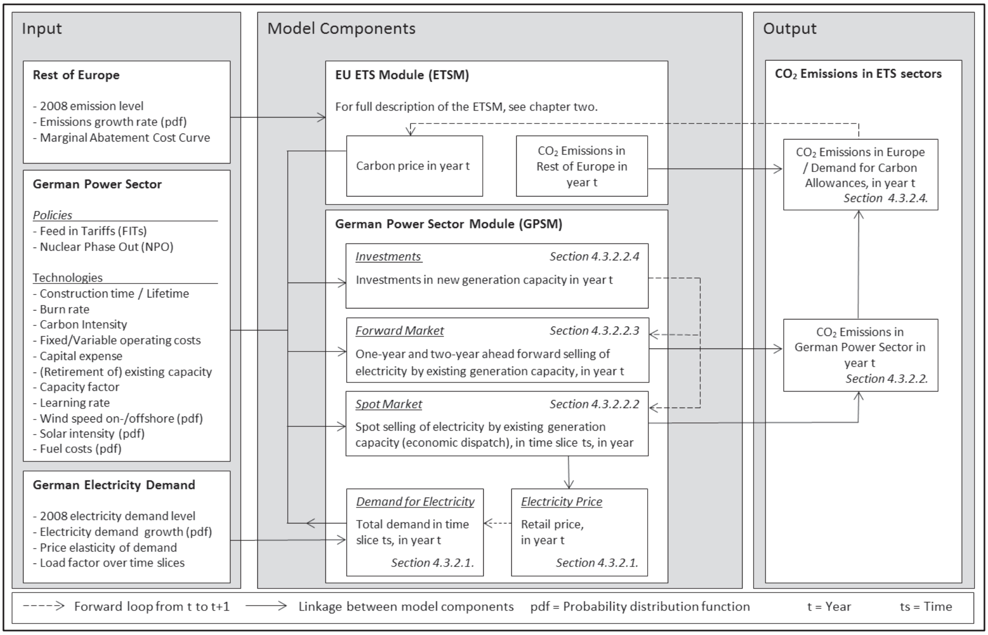
Our model does capture the impact of the allowance banking mechanism because we simulate the EU ETS over a longer time horizon (2008-2030). Apart from the allowance banking mechanism, the chosen time horizon is sufficiently long to capture the impact of all the examined instruments on investment behaviour and, thereby, the long term CO_2 emission output of the German power sector. Key dynamic and interacting parameters (among others parameters that are dependent on the rate of economic growth) are modelled stochastically over time. As a result, we expect to be able to draw a more complete and accurate picture of the impact of the German FITs and NPO on the performance of the EU ETS.

The insights that are obtained via this study can be particularly valuable to policymakers. Specifically, the probabilistic analysis can help policymakers to assign weights to potential interaction effects when they consider the introduction of FITs or a NPO alongside an ETS. Because this study is specifically tailored to the German case, direct extrapolation of the results to other (future) policy settings is not possible. However, the results may provide a deeper insight in the dynamics and vulnerabilities of a policy mix with this composition.

4.3. Methodology

The methodology section is divided into three main sections. In Section 4.3.1 we provide a general description of the model design and components. Also, we explain how instruments are expected to affect the carbon price and the emission level via each of the model components. Subsequently, in Section 4.3.2 we provide the mathematical description of the model. Finally, in Section 4.3.3 we layout the 8 scenarios that are tested.

Figure 4.1: Model overview



4.3.1. General description

The model, as shown in Figure 4.1, consists out of two key components: an EU ETS module (ETSM) and a module for the German power sector (GPSM). Based on the CO_2 emission level in the previous year $(t-1)$, the ETSM calculates the equilibrium carbon price for year t of the simulation.[31] Information from a previous year $(t-1)$ that is used in year t is indicated in Figure 4.1 with a forward loop. Based on the equilibrium carbon price, the GPSM determines the spot and forward selling of electricity, investments in new generation capacity, the retail electricity price and electricity demand. Together, they determine the emission output of the German power sector and the emission output of all other sectors that are covered by the EU ETS throughout Europe in year t.

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[31] In reality, the accounting process to verify the level of CO_2 emissions around Europe takes several months to complete. As a result, the emission level over the year $t-1$ is publicly announced via the European Commission around April of year t. We assume that this information is available at the start of year t.

A detailed description of the ETSM, and the manner in which the annual equilibrium carbon price is determined, can be found in Chapter 2. Below, we will describe the GPSM, and the manner in which it is linked to the ETSM, in detail. Figure 4.1 is a simplified representation of the model. The arrows only indicate key interactions between the different model components. Costs and prices are all denoted in 2010 euros.

The input parameters of the ETSM and GPSM are outlined on the left in Figure 4.1. The abbreviation pdf indicates which input parameters are modelled stochastically.[32] A more detailed overview of all stochastic parameters is provided in Table 4.1. The table outlines nine stochastic parameters, divided over four classes. For example, the growth rates of the demand for electricity (in Germany) and the emission level (in the rest of Europe) belong to the same class because they are both dependent on the rate of economic growth. The probability distributions that are associated to the stochastic parameters are described in the sections indicated in column four of Table 4.1.

Our procedure is as follows. We sample a value from the probability distribution of a stochastic parameter for each relevant time step between 2008 and 2030 (see column 3 of Table 4.1). For example, emission growth rates that are dependent on economic growth are sampled for each year in the interval (implying 23 samples for the German electricity demand growth rate). Wind speed and solar irradiance levels are sampled for each hour in the interval (implying 201,480 samples for offshore wind speeds). The fuel price growth rate is sampled for each season in the interval (implying 92 samples for the rate of change in the oil price).

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[32] Other model parameters that are uncertain/unknown and could affect the model output will be covered in the sensitivity analysis.

Table 4.1: Stochastic input parameters

Class	**Parameter**	**Sampled for every …. time Step**	**Section**	**Equation**
Economic growth	Electricity demand growth in Germany	Yearly (t)	4.3.2.1.	4.1
	Emission growth rate in the Rest of Europe	Yearly (t)	4.3.2.4	4.49
Wind power	Onshore wind power	Hourly (h)*	4.3.2.2.1	4.6
	Offshore wind power	Hourly (h)*	4.3.2.2.1	4.6
Solar irradiance	Solar irradiance	Hourly (h)*	4.3.2.2.1	4.8
Fuel prices	Coal price	Seasonal (s)**	4.3.2.2.2	4.19
	Gas price	Seasonal (s)**	4.3.2.2.2	4.19
	Uranium price	Seasonal (s)**	4.3.2.2.2	4.19
	Oil price	Season (s)**	4.3.2.2.2	4.19

*Note that the smallest time step in the GPSM is a time slice (ts) that consists out of 547.5 hours (see Table 9.1, column 1-3, for an overview of all time slices). To find the wind speed/solar irradiance level for a single time slice we take the average over 547.5 samples. See below in this section for a detailed explanation on time slices.
**A season consists out of 4 time slices.

We perform a Monte Carlo procedure by repeating this process 2,000 times. By combining the model output of all 2,000 model runs, we obtain a probability distribution of the future emission level in Germany as well as the carbon price. As opposed to a fully deterministic approach, the Monte Carlo simulation allows us to determine to what extent abatement activity is driven by forces that are outside the control of policymakers and operators in the electricity market.

The ETSM and GPSM modules forecast the emission level and abatement activity between 2008 and 2030, but do so using different time steps. The ETSM uses annual time steps, while each year is divided up into 16 time slices in the GPSM. A time slice represents a portion of a typical day (night, morning, afternoon or evening) in one of the four seasons. An overview of all time slices is provided in the first three columns of Table 9.1 in the Appendix.

We divide up the year in this manner because, as opposed to the carbon price, the electricity price pattern is characterized by seasonality and alternations between day and night. Consequently, the profitability of investments in a technology depends greatly on the exact moments in a year during which a technology is expected to be operational. We therefore need time slices that are small enough to capture seasonal and daily variation in the production mix and electricity price.

The hours in a year are grouped in time slices such that seasonal and daily trends can be captured while maintaining computational efficiency. Note that the manner of grouping the hours implies that the time slices do not have a sequential order from 1 to 16. For example, time slice number 10 captures all hours that fall in the summer afternoon; the hours between 12:00-18:00pm over three months. Given that a typical year exists out of 365*24=8,760 hours, each of the 16 time slices represents 8,760/16=547.5 hours. Although the time slices are relatively large (some power market models use hourly, sequential, time steps) this method does not lead to a significant loss of detail. To see why, consider that the composition of the production mix may vary over the 547.5 hours that are grouped in a single time slice. If the mix of electricity generating technologies changes, the emission level also changes. A primary driver of these variations is the uncertain availability of solar and wind power. If the model would be deterministic, such variations would not be accounted for and lead to a great loss of detail. However, because we perform 2,000 Monte Carlo model runs, and sample solar and wind speeds from a probability distribution for each run, relatively large time slices can be used without a significant loss of detail. Using smaller time steps would primarily lead to a significant increase in the computation time of the model. Individual time slices are denoted by ts. A year is denoted by t. Finally, seasons are subsets of 4 time slices and are denoted by s. See Table A.1 in the Appendix for an overview.

Having explained the key input parameters, the Monte Carlo procedure, and the different time steps/slices in the two modules of the model, we will now describe the manner in which the ETSM and GPSM modules interact, as illustrated in Figure 4.1. Specifically, we explain the ways in which the introduction of a carbon price (ETSM) is expected to affect the emission output of the German power sector (GPSM). Subsequently, we explain the concept behind the two parallel instruments that are under study (FITs and the NPO) and the manner in which these instruments are expected to affect the carbon price (ETSM).

The introduction of a carbon price (ETSM) affects abatement activity in the German power sector (GPSM) in three ways: via the spot market, via the forward market and via investments in new generation capacity. All three will now be discussed in more detail.

Carbon price impact on the spot market - The spot market functions on the basis of economic dispatch. Economic dispatch entails that owners of generation capacity place bids, based on their marginal production costs, to obtain production blocks. The technologies with the lowest marginal cost are dispatched first, until enough capacity is dispatched to meet the spot demand in each time slice. If a carbon price is introduced, operators of CO_2 emitting technologies will experience higher marginal productions costs. As a direct result, the probability that a carbon-intensive technology will become operational via economic dispatch falls. If carbon intensive technologies do become operational, the higher marginal production costs will generally result in a higher electricity price because the electricity price is determined by the producer with the highest marginal production costs. A higher electricity price will lower the demand for electricity. Both possible effects, lower reliance on carbon-intensive technologies or a lower demand for electricity via a higher electricity price, reduce the CO_2 emissions of the German power sector.

Carbon price impact on the forward market –The effects of a carbon price on the forward market are similar to those on the spot market. We assume that operators can sell electricity one or two years ahead of production on the forward market. That is, operators can sell forward contract in year $t-1$ or $t-2$ to produce a specified amount of electricity in year t. By selling on the forward market, operators gain certainty about the production level and revenue in a future period. What type of generation capacity is sold forward (*e.g.* hydro, coal-fired or gas-fired capacity) depends on the forecasts of the electricity price and the marginal production costs of each technology. The lower the marginal production costs, the easier it is for operators to sell their electricity forward at a profit. The carbon price will increase the marginal production costs of CO_2-emitting technologies. Thereby, the introduction of a carbon price makes it harder for operators to sell their electricity forward in a profitable manner. Consequently, the carbon intensity of the electricity that is sold via the forward market is expected to fall. Note that the introduction of a carbon price in year t will not affect the forward production in year t itself because those contracts were already negotiated in year $\mathrm{t}-1$ and $\mathrm{t}-2$. However, it can affect new forward contracts with a production date in the year $\mathrm{t}+1$ or $\mathrm{t}+2$.

Carbon price impact on investments – Because a carbon price increases the operating costs of CO_2-emitting technologies, and reduces the probability that those technologies will be operational via both the spot and forward market, the net present value of investments in CO_2-emitting technologies is expected to fall. Consequently, the level of investments in CO_2-intensive technologies is expected to decline. At the same time, the introduction of a carbon price increases both the price of electricity and the probability that dispatchable renewable technologies will become operational. Thereby, the carbon price also, indirectly, stimulates investments in renewable technologies. Through discouragement of investments in carbon-emitting technologies, and indirect support for investment in renewable technologies, the introduction of a carbon price is expected to have a downward effect on future emission levels via investments.

In sum, the carbon price (ETSM) is expected to lead to a lower emission level in the German power sector (GPSM). The anticipated effects via the spot market, forward market and investments are unidirectional, and point to increased CO_2 abatement activity.

We will now discuss the anticipated effects of introducing two parallel instruments in the German power sector (GPSM) on the carbon price (ETSM). The introduction of a NPO and FITs (GPSM) affects the carbon price (ETSM) in a variety of ways, which will be discussed below. Note that we discuss the anticipated effects under the assumption that a carbon price is already in place, and that one of the parallel instrument is added to that policy setting. In general, both parallel instruments affect the carbon price indirectly via the emission output of the German power sector. If a parallel instruments leads to an overall increase in the emission level, the carbon price is expected to increase. If the overall emission level decreases further after the introduction of a parallel instrument, the carbon price is expected to fall. First, we discuss the expected effects of introducing a NPO, followed by a discussion of the expected effects of introducing FITs.

NPO impact on the carbon price – The NPO refers to the timetable that was set up by the German government to decommission all nuclear generation capacity before the end of 2022. The timetable specifies when each plant is set to be decommissioned. The first plants were decommissioned in 2011, with others following in 2015, 2017, 2019, 2021 and 2022. The effect of the NPO on the emission level depends on the technology that replaces the nuclear capacity. Nuclear electricity generation has a relatively low CO_2 intensity (0.016 tCO_2/MWh versus 0.4 and 0.9 tCO_2/MWh for gas and coal fired plants respectively). The emission level is therefore likely to increase if nuclear power is replaced by conventional thermal generation technologies. However, if nuclear technology is replaced by renewable technology with a lower carbon intensity –nuclear generation technology has a CO_2 intensity of 0.016 tCO_2/MWh - a phase out may lead to a slight fall in emissions, although such a fall would be hardly noticeable.

Conventional thermal generation capacity is readily available in Germany, while the capacity of renewable electricity production is currently too low to fully replace the nuclear power capacity. Therefore, we expect both higher emissions and a higher carbon price in the short term. The long-term effect on the emission level depends on the rate of investments in renewable technologies. Other effects of the NPO are (1) a higher electricity price (because a relatively cheap abatement option is replaced by technologies with higher marginal production costs) and (2) a lower demand level (in response to the higher electricity price).

Overall, a NPO is likely to provide upward pressure for the emission level and carbon price in the long run. However, if the higher electricity price triggers large investments in renewables alongside a drop in the demand for electricity, the upward pressure on the emission level and carbon price may be partly or fully compensated for.

FITs impact on the carbon price – FITs offer investors in renewable generation technologies the opportunity to sell their electricity at a predetermined fixed price for 20 years. Also, investors are offered priority dispatch. This means that operators are not dependent on the economic dispatch system on the spot market, but have guaranteed access to the grid. In other words, any electricity that is produced can be sold directly against the predetermined price. Given these clear advantages, FITs are expected to boost the deployment of renewable technologies, lower the emission level and provide downward pressure on the carbon price. FITs are also expected to significantly increase the retail electricity price, because FITs are financed through a mark-up on the retail electricity price. The predetermined price that is offered to producers is thereby fully paid for by consumers. A higher electricity price will reduce the demand and provide further downward pressure on the emission level. All in all, the anticipated effect of FITs on the carbon price is clear: the carbon price is expected to depreciate because of a combination of higher deployment rates of renewables and a reduction of the demand for electricity.

4.3.2. Mathematical description of the GPSM

In this section, we formalize the model. The main aim is to develop the GPSM module that determines the emission output of the German power sector. Subsequently, we link the GPSM to an existing module that determines the EU ETS-based carbon price (ETSM). By linking the GPSM and the ETSM, we are able to determine interaction effects between instruments in the German power sector, the EU ETS carbon price and the emission level.

To determine the emission output of the German power sector, we first define the demand for electricity in Section 4.3.2.1. The supply of electricity is formalized in Section 4.3.2.2. The equilibrium between the demand and supply for electricity depends on the available generation capacity (formalized in Section 4.3.2.2.1), and is ultimately determined on both the spot market (Section 4.3.2.2.2.) and the forward market (Section 4.3.2.2.3). The production mix in future periods is in part driven by investments in new generation capacity (section 4.3.2.2.4). We define how FITs and the NPO are modelled in Section 4.3.2.3. Finally, we formalize how the GPSM and ETSM modules are integrated in Section 4.3.2.4

4.3.2.1. DEMAND FOR ELECTRICITY

The demand for electricity determines how much electricity needs to be produced. Obviously, there is a positive relationship between the demand for electricity and the level of CO_2 emissions. We do not discriminate between types of consumers (households, industry, commerce, etc.), but only determine the total demand for electricity in MWh. The total demand for electricity in year t is denoted by:

$$TD_t = TD_{t-1} * (1 + ELG_t) * (1 + \frac{RE_{t-1} - RE_{t-2}}{\frac{RE_{t-1} + RE_{t-2}}{2}} * -0.2) \qquad for\ t = [2008, \ldots, 2030] \qquad (4.1)$$

Total demand in year t (in MWh) is calculated by multiplying total demand in the previous year (TD_{t-1}) by two terms: the rate of growth of electricity demand (ELG_t), and a correction for the arc price elasticity[33] of demand. The former term captures changes in the demand for electricity that are driven by economic growth whereas the latter term captures changes in the demand for electricity that are driven by the level of the retail electricity price (RE).

ELG_t represents the growth in electricity demand. ELG_t is sampled from a normal distribution[34] with mean 0.5% and standard deviation 1.09%. The mean is in line with the projection of the Institut für Energiewirtshaft und Rationelle Energieanwendung between 2007 and 2030 (IER, 2010). We calculated the standard deviation on the basis of German electricity demand between 1994 and 2008 (BWT, 2013). To represent the impact of the recession that started in 2008, the input values for ELG_t over the period 2008-2012 have been set deterministically based on historical data.

The demand correction for the arc price elasticity of demand is calculated based on the change in the retail electricity price in the previous year. We assume an elasticity of demand of -0.2, in line with other studies on the German power sector (see *e.g.* Sijm *et al.*, 2006 and Hobbs *et al.*, 2005). This implies a demand response of -0.2% for a 1% increase (based on arc-elasticity) of the retail electricity price.

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[33] The arc price elasticity means that the change in the retail price is denoted relative to the midpoint between the retail prices in $t-1$ and $t-2$. As a result, the demand response is symmetric, irrespective whether the price changes from, for example 21ct./KWh to 23 ct./KWh or vice versa.

[34] The number of historical data points is limited and therefore the exact shape of the probability distribution cannot be estimated with great certainty. Using a Chi-square goodness-of-fit test we were unable to reject a normal distribution at the 5% significance level.

The retail electricity price in year t is defined as:

$$RE_t = \frac{\left(\sum_{ts=1}^{16} E_{ts,t} SD_{ts,t}\right)}{\sum_{ts=1}^{16} SD_{ts,t}} + 160 \qquad for\ t = [2008, \dots, 2030] \qquad (4.2)$$

The retail electricity price (in €/MWh) is equal to the sum of two terms: the weighted average spot electricity price and other costs. Other costs include network costs as well as taxes and levies (excluding those related to the FIT-scheme). In 2008, these other costs amounted to approximately €160 per MWh (BDEW, 2013; Gerbert *et al.*, 2013). In order not to overly complicate the analysis, we assume that other costs remain constant over time.

E represents the spot electricity price (in €/MWh) in time slice ts in year t, SD represent the spot demand for electricity (in MWh) in that same time slice. Both E and SD will be further defined in Section 4.3.2.2.2 on the spot market.

The demand for electricity, as defined in Equation 4.1, is not constant throughout the year. For example, the demand for electricity if higher in the winter compared to the summer. Also, the demand is higher in the afternoon and evening compared to the night and morning. We account for this in Equation 4.3. The electricity demand in time slice ts in year t is defined as:

$$D_{ts,t} = TD_t * LF_{ts} \qquad for \quad ts = [1, \dots, 16],\ t = [2008, \dots, 2030] \qquad (4.3)$$

Total demand (TD_t) is multiplied by the load factor for time slice ts (LF_{ts}).[35] The 16 load factors sum to 1 and are provided in column four of Table 9.1 in the Appendix. Data sources are specified in Table 9.1 as well.[36]

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[35] Note that ts is a single index (and abbreviation) of a time slice. It is distinct from the index t, which captures an entire year.

4.3.2.2. SUPPLY OF ELECTRICITY

A mix of electricity generation technologies is used to meet the demand for electricity. The exact composition of the production mix determines the level of CO_2 emissions. The composition of the production mix depends on two factors: the availability and the generation costs of each technology. In Section 4.3.2.2.1 we formalize the availability of generation capacity of each technology. In Sections 4.3.2.2.2 and 4.3.2.2.3 we formalize the production costs of each technology to calculate which technologies supply electricity via the spot and forward market respectively. Finally, in Section 4.3.2.2.4, we determine the level of new investments in each technology based on their profitability.

4.3.2.2.1. Generation Capacity

In this study, we distinguish between 22 generation technologies. See Table 9.2 for an overview. The available generation capacity of technology i in MW in year t is defined as:

$$CAP_t^i = CAP_{t-1}^i - RET_t^i + INV_{t-CT^i}^i \qquad for \quad i = [1, \ldots, 22],\ t = [2008, \ldots, 2030] \tag{4.4}$$

Here, CAP_{t-1}^i is the generation capacity of technology i in the previous year, minus the capacity that is retired in year t ($RET_{i,t}$), plus new investments ($INV_{i,t-CT_i}$) in technology i that come on stream in year t. CT_i is de construction time of a typical plant of technology i (see column 4 of Table 9.2 in the Appendix for input values). New investments are defined endogenously and will be specified later in Section 4.3.2.2.4.

The generation capacity in the first year of the simulation and the retirement schedule are exogenous input to the model. The generation capacity in 2008 is shown in column 5 of

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[36] In Section 4.3.2.2.2. we distinguish between consumers who buy electricity via the spot market (equal to $SD_{ts,t}$) and those that buy electricity via the forward market (equal to $\sum_{i=1}^{22} FORP_{ts,t}^i$). The total demand for electricity in a specific time slice ($D_{ts,t}$) is equal to the sum of spot demand ($SD_{ts,t}$) and forward demand ($\sum_{i=1}^{22} FORP_{ts,t}^i$).

Table 9.2 in the Appendix. The retiring schedule between 2008 and 2030 is displayed in Figure 9.1 in the Appendix. Some technologies are not included in Figure 9.1. This is due to one of two reasons: either no capacity was deployed in 2008, or no capacity is projected to be retired before 2030. We estimated the retiring schedule of the existing portfolio on a plant-level (UB, 2014), based on the year of construction, the generation capacity and the assumed technical life time (column 6 in Table 9.2) of each plant. The most detailed plant-level data that we are aware of (UB, 2014) also specified if plants underwent a technical upgrade at some point since their first commissioning. We assume that, if such an upgrade was performed, it extends the technical lifetime of a plant by 70%. We calibrated this percentage such that the calculated operational capacity for 2008 matches the actual 2008 levels, as specified in column 5 of Table 9.2. Upgrading an existing plant is not an investment option in the model. We only accounted for upgrading to generate the retirement schedule. Regarding nuclear generation capacity, we have brought the retirement schedule in line with existing retirement planning before the introduction of the NPO (Bundestag, 2010).

Column 7 in Table 9.2 specifies the year in which a technology is introduced to the power market model. For example, Carbon Capture and Storage (CCS) is assumed to be technically ready to be introduced in 2025. Before that year, CCS technology will not be deployed. Similarly, a new type of Biomass technology (CHP and dedicated) is assumed to become available in 2015 alongside the conventional biomass technologies.

Equation 4.4 defines the available technical generation capacity in MW for each technology. However, none of the technologies is able to utilize 100% of the technical generation capacity at any time during the year. Intermittent sources of electricity supply are dependent on the availability of wind power and solar irradiation levels. Also, thermal plants generally never operate above 95% of the installed capacity. Other dispatchable sources of electricity supply are dependent on the supply of resources (*e.g.* water, biomass or biogas) which may not always be available. To account for this limit, a capacity factor is specified for each technology. The capacity factor indicates the maximum operational capacity as a fraction of the rated capacity. For example, a technology with an installed capacity of 2 GW and a capacity factor of 0.95 has a maximum operational capacity of 1.9 GW. For dispatchable technologies, the capacity factor is constant over time and is provided in column 8 of Table 9.2. Using the capacity factor, we can determine the production factor (PF). The production factor is used to convert MW of installed generation capacity into the maximum production level in MWh per technology i:

$$PF^{i} = CAPF^{i} * 547.5 \qquad for\ i = \{5, \dots, 22\} \tag{4.5}$$

The above formula holds for all dispatchable technologies ($i = \{5,..,22\}$). Note that we multiply by 547.5 because there are 547.5 hours in a time slice. In the remainder of this section we specify the production factor for intermittent technologies ($i = \{1,..,4\}$), which are modelled stochastically. In the following section (Section 4.3.2.2.2) we use the production factor PF to determine the production mix on the spot market.

Wind power - The production and capacity factor for wind turbines depends on a stochastically sampled wind speed, and the technical parameters of the wind turbine. We assume a typical 80 meter high wind turbine, with cut in, rated and cut off wind speed of 3, 12 and 25 meter/second. These parameters indicate that the turbine starts producing electricity if the wind speed is greater than 3 m/s, and is shut down if the wind speed surpasses 25 m/s. The turbine is able to produce at full capacity between 12 and 25 m/s.

The capacity factor of wind powered technology during an hour h in time slice ts in year t is defined as:

$$CAPF_{h,ts,t}^{i} = \begin{cases} 0 & if\ \omega_{h,ts,t}^{i}(\lambda_{ts}^{i}, \kappa_{ts}^{i}) < 3\ \ or\ \omega_{h,ts,t}^{i}(\lambda_{ts}^{i}, \kappa_{ts}^{i}) > 25 \\ \frac{\omega_{h,ts,t}^{i}(\lambda_{ts}^{i}, \kappa_{ts}^{i}) - cutin}{rated - cutin} & if\ 3 \le \omega_{h,ts,t}^{i}(\lambda_{ts}^{i}, \kappa_{ts}^{i}) \le 12 \\ 1 & if\ 12 \le \omega_{h,ts,t}^{i}(\lambda_{ts}^{i}, \kappa_{ts}^{i}) \le 25 \end{cases}$$

$$for\ i = \{1,2\},\ h = [1, \ldots, 548],\ ts = [1, \ldots, 16],\ t = [2008, \ldots, 2030] \quad (4.6)$$

A graphical representation of Equation 4.6 is shown in Figure 9.2 in the Appendix. The capacity factor is zero if the stochastically sampled wind speed ($\omega_{h,ts,t}^{i}$) is either lower than the cut-in wind speed, or higher than the cut-off wind speed. If the wind speed is in between the cut-in and rated wind speeds, we assume that the capacity factor rises linearly from zero to one. Finally, the capacity factor is equal to one if the stochastically sampled wind speed is both greater than the rated wind speed, and lower than the cut-off wind speed.

The wind speed is stochastically sampled from a Weibull distribution with scale parameter λ_{ts}^{i} and shape parameter κ_{ts}^{i}.[37] The distributions differ strongly for onshore ($i = 1$) and offshore ($i = 2$) wind speeds. Offshore wind speeds are generally higher. This is reflected in the input data provided in columns 5-8 of Table 9.1. In each time slice, the values of the scale and shape parameters are the greatest for offshore wind, when compared to those of onshore wind. Data sources are provided below Table 9.1.

Equation 4.6 defines the capacity factor for a single hour within a time slice. There are 547.5 hours in a time slice. Therefore, we take a sample for each hour, and sum the obtained capacity factors to determine the production factor of technology i in time slice ts in year t:

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[37] Aksoy *et al.*, 2004 show that Weibull distributions accurately capture the variability in wind speeds. We estimated the Weibull distribution parameters using the maximum likelihood method because this method is considered most appropriate (Seguro and Lambert, 2000). Data sources are provided in Table 9.1.

$$PF_{ts,t}^{i=\{1,2\}} = \sum_{h=1}^{547} CAPF_{h,ts,t}^{i} + CAPF_{h=548,ts,t}^{i} * 0.5$$

$$for\ i = \{1,2\},\ ts = [1,\dots,16],\ t = [2008,\dots,2030] \tag{4.7}$$

Note that the 548th sample is multiplied by 0.5 to account for the final half hour in the time slice.

Solar Irradiation - For technologies based on solar radiation, the capacity factor depends on the amount of solar irradiation that reaches the earth's surface (in Watt/m^2). A simple, yet accurate, way to infer the capacity factor of solar-based technologies is by using the clearness index (Kumar and Umanand, 2005). The clearness index is the ratio between the solar irradiation that reaches the earth's surface (in W/m^2) and the solar irradiation level just outside the earth's atmosphere (in W/m^2). The latter is assumed constant at 1,360 W/m^2. The former, the amount of irradiation that reaches the earth's surface, depends strongly the humidity of the air, dust particles, the season and the time of day. Average surface level irradiance data in Germany for each time slice was taken from Photovoltaic Geographical Information System (PVGIS) of the European Commission Joint Research Centre. The data is provided in column 9 of Table A.1.

Based on the average clearness index in each time slice (g_{ts}) we use a modified gamma distribution to accurately capture the hourly variability of the clearness index (Hollands and Huget, 1983). The general form of the modified gamma distribution if derived by Hollands and Huget (1983):

$$P\left(CAPF_{h,ts,t}^{i}, g_{ts}\right) = \partial_{ts} \frac{c_{max} - CAPF_{h,ts,t}^{i}}{c_{max}} \exp(\nu_{ts} CAPF_{h,ts,t}^{i})$$

$$for\ i = \{3,4\},\ h = [1,\dots,548],\ ts = [1,\dots,16],\ t = [2008,\dots,2030] \tag{4.8}$$

$CAPF_{h,ts,t}^{i=\{3,4\}}$ is the sampled capacity factor for a single hour. g_{ts} is the mean clearness index and c_{max} is the upper bound to the clearness index, which is set at 0.864 (Hollands and Huget, 1983). An upper bound indicates that some solar irradiance is always absorbed by, or scattered in, the earth's atmosphere, even on day with clear blue skies. ∂_{ts} and ν_{ts} are the scale and shape parameters of the gamma distribution. The values of ∂_{ts} and ν_{ts} are dependent upon the mean clearness index g_{ts}. For a derivation of this relationship we refer to the original paper. We calculated the values of ∂_{ts} and ν_{ts} for all time slices, and provide them in columns 10 and 11 of Table 9.1.

Based on these parameters, we constructed the cumulative probability distributions of the clearness index for each time slice and depicted them in Figure 9.3. The distributions for evenings and nights are not depicted. Average solar irradiance levels during evenings and nights are mostly zero (0.01 in the summer). Therefore, we assume a fixed capacity factor of 0 during all of these time slices.

Finally, similar to the methodology for wind power, we take samples from the modified gamma distribution for all 547.4 hours in a time slice. We sum the obtained capacity factors to obtain the production factor for solar based technologies in time slice ts in year t:

$$PF_{ts,t}^{i} = \sum_{h=1}^{547} CAPF_{h,ts,t}^{i} + CAPF_{h=548,ts,t}^{i} * 0.5$$

$$for\ i = \{3,4\},\ ts = [1, \dots, 16],\ t = [2008, \dots, 2030] \tag{4.9}$$

4.3.2.2.2. Spot Market

In this section, we describe the manner in which the spot market is modelled. The economic dispatch procedure on the spot market ensures that the supply of electricity equals the total demand for electricity at any point in time. In the process, the equilibrium spot electricity price is determined. The equilibrium spot electricity price depends on the marginal production costs of the available production technologies and on the level of demand on the spot market.

The description of the spot market is divided into multiple steps. First, we lay out the interactions of the spot market with the forward market. The spot and forward market are collectively exhaustive: their sum covers the entire supply of, and demand for, electricity. The greater the forward market, the smaller the spot market. Secondly, we describe the economic dispatch procedure, which determines the production volume of each production technology. Third, we define how the CO_2 emission level is calculated. Fourth, we derive the spot electricity price based on the production volumes that were determined via the economic dispatch procedure. In the final steps we specify the drivers behind the marginal production costs of each technology. The drivers behind the marginal production costs are divided into three cost components: the emission costs, the fuel costs and other operating costs. Each of these cost components is separately discussed.

Interactions with the forward market – Producers can sell electricity via either the spot or the forward market. If producers sold electricity forward in earlier years that is due for production and delivery in time slice ts, generation capacity is needed to do so. As a result, the generation capacity that is available for production on the spot market is lower than the maximum operational capacity, as defined in Equation 4.4. Similarly, the demand for electricity on the spot market is lower than the total demand in time slice ts if some consumers have bought electricity on the forward market one or two years ago. First, we formalize these interactions between the spot and forward market. The demand for electricity on the spot market in time slice ts in year t is defined as:

$$SD_{ts,t} = D_{ts,t} - \sum_{i=1}^{22} FORP_{ts,t}^{i} \qquad for\ ts = [1, \ldots, 16],\ t = [2008, \ldots, 2030] \qquad (4.10)$$

The spot demand for electricity ($SD_{ts,t}$) is equal to the total demand for electricity ($D_{ts,t}$) minus the electricity that was sold via the forward market and set for delivery in time slice ts in year t ($\sum_{i=1}^{22} FORP_{ts,t}^{i}$). At the beginning of year t, $\sum_{i=1}^{22} FORP_{ts,t}^{i}$ is a known quantity (because it is based on production contracts that were signed in previous periods). We will further define $\sum_{i=1}^{22} FORP_{ts,t}^{i}$ in Section 4.3.2.2.3 on the forward market. All terms in Equation 4.10 are denoted in MWh of electricity.

The production capacity of technology i that is available on the spot market (in MWh) in time slice ts in year t is defined as:

$$SP_{ts,t}^{i} = CAP_{t}^{i} * PF_{ts,t}^{i} - FORP_{ts,t}^{i} \qquad for\ i = [1, \ldots, 22],\ ts = [1, \ldots, 16],\ t = [2008, \ldots, 2030] \qquad (4.11)$$

Here, CAP_{t}^{i} is the installed generation capacity (in MW, see Equation 4.4) and $PF_{ts,t}^{i}$ is the production factor of technology i (to convert MW into MWh of generation capacity per time slice). Finally, we subtract any electricity that is produced for the forward market by technology i ($FORP_{ts,t}^{i}$).

$$if\ \ SD_{ts,t} \geq \sum_{i=1}^{22} SP_{ts,t}^{i} \qquad SD_{ts,t} - \sum_{i=1}^{22} SP_{ts,t}^{i} = import_{ts,t}$$

$$for\ ts = [1, \ldots 16],\ t = [2008, \ldots, 2030] \qquad (4.13)$$

If the spot demand is greater or equal than the available production capacity, all technologies produce at full capacity. In that case, the difference is assumed to be imported from abroad ($import_{ts,t}$). Imports may be required if new investments in generation capacity cannot keep up with the retirement of old capacity.

Economic Dispatch – If the spot demand is lower than the available production capacity ($SD_{ts,t} < \sum_{i=1}^{22} SP_{ts,t}^{i}$), the production level of each technology is determined via economic dispatch.[38] Economic dispatch entails that the production technologies with the lowest marginal production costs are dispatched first, until enough capacity is dispatched to meet the spot demand for electricity. The spot market can therefore be specified as a linear optimization problem with two constraints that is solved for $P_{ts,t}^{i}$, the production level in MWh of technology i in during time slice ts in year t:

$minimize$

$$\sum_{i=1}^{22}(MC_{ts,t}^{i} * P_{ts,t}^{i}) \qquad for\ ts = [1,\dots,16],\ t = [2008,\dots,2030] \qquad (4.12.1)$$

$subject\ to$

$$0 \leq P_{ts,t}^{i} \leq SP_{ts,t}^{i} \qquad for\ i = [1,\dots,22],\ ts = [1,\dots,16],\ t = [2008,\dots,2030] \qquad (4.12.2)$$

$$\sum_{i=1}^{22} P_{ts,t}^{i} = SD_{ts,t} \qquad for\ i = [1,\dots,22],\ ts = [1,\dots,16],\ t = [2008,\dots,2030] \qquad (4.12.3)$$

Here, $MC_{ts,t}^{i}$ is the marginal production cost of technology i (in €/MWh). The marginal production cost of each technology is known at the beginning of every time slice and will be explained in full detail below. $P_{ts,t}^{i}$ is the spot production of technology i in MWh. Two constraints are in place. First, the production level of technology i ($P_{ts,t}^{i}$) is constrained by a lower bound of zero and an upper bound equal to $SP_{ts,t}^{i}$ (as defined in Equation 4.11). The second constraint specifies that the total production of all Z technologies should equal the spot demand in each time slice.

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[38] In our model, exports are disregarded. Exporting electricity is only theoretically possible (namely, if the cumulative supply of electricity by intermittent resources – wind and solar - during a time slice ts is larger than the demand in that same time slice). However, the probability of such an event is negligible because, first, a time slice covers a total of 547.5 hours (supply peaks from wind and solar are thereby smoothened) and, secondly, penetration levels of intermittent technologies by 2030 are generally not sufficiently high.

Emission level – Based on the production level in the spot and forward market, the emission level of the German power sector in year t is:

$$EM_t = \sum_{i=1}^{22}\left[\sum_{ts=1}^{16}\left(P_{ts,t}^{i} + FORP_{ts,t}^{i}\right) CI^{i}\right]/1{,}000{,}000 \qquad for\ t = [2008, \ldots, 2030] \tag{4.14}$$

The emission level is the sum of spot and forward production, multiplied by the carbon intensity of each technology (CI^i in tCO$_2$/MWh). CI^i is exogenous input and provided in column 9 of Table 9.2.[39] We divide by 1,000,000 so that EM_t is denoted in million tonnes of CO$_2$ (MtCO$_2$).

Spot electricity price - Given $P_{ts,t}^{i}$, we can determine the spot electricity price (in €/MWh) during time slice ts in year t:

$$E_{ts,t} = \max_i\left(MC_{ts,t}^{i} \middle| P_{ts,t}^{i} > 0\right) \qquad for\ ts = [1, \ldots, 16],\ t = [2008, \ldots, 2030] \tag{4.15}$$

The spot price for electricity ($E_{ts,t}$) is equal to the marginal production costs of the most expensive technology that is operational ($P_{ts,t}^{i} > 0$) during time slice ts in year t. Equations 4.10 to 4.15 capture the key mechanism behind the spot market. Also, we defined one of the key output parameters of the model: the emission level of the German power sector (EM_t). The remainder of this section is devoted to a further explanation on the marginal production costs ($MC_{ts,t}^{i}$). So far these costs were assumed to be known, but we will now explain how they are determined.[40]

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[39] A limitation of our study is that we do not account for the possibility that the carbon intensity of technologies may fall through innovation.

[40] Note that the production levels do not depend on the capital expense that is incurred by operators. Fixed costs are paid for via operating profits (electricity price – marginal production costs).If operators invest in a technology, they anticipate enough operating profits over the lifetime of the technology to cover the capital expense.

Marginal production costs – The economic dispatch procedure and the calculation of the spot electricity price depend on the marginal production costs of technology i during time slice ts in year t ($MC^i_{ts,t}$):

$$MC^i_{ts,t} = EC^i_t + FC^i_{ts,t} + OC^i \qquad for\ \ i = [1,\dots,22],\ ts = [1,\dots,16],\ t = [2008,\dots,2030] \qquad (4.16)$$

The marginal production cost of technology i ($MC^i_{ts,t}$) is the sum of the cost of emitting CO_2 emissions ($EC^i_{ts,t}$), the costs of fuel use ($FC^i_{ts,t}$) and other operating costs (OC^i). Each of these components will now be explained in detail.

The costs of emitting CO_2 ($EC^i_{ts,t}$) - The cost of emitting CO_2 (in €/MWh) of technology i during year t is defined as:

$$EC^i_t = CI^i * FCPI_t \qquad for\ \ i = [1,\dots,22],\ t = [2008,\dots,2030] \qquad (4.17)$$

Here, CI^i is the carbon intensity of technology i and $FCPI_t$ is the carbon price in year t (in €/tCO_2).[41] The carbon price is an endogenous model parameter, calculated in the ETSM module. A full description of the ETSM module is provided in Chapter 2.

The costs of fuel use ($FC^i_{ts,t}$) - The costs of fuel use (in €/MWh) of technology i during time slice ts in year t is defined as:

$$FC^i_{ts,t} = FP^i_{ts,t} * \beta^i \qquad for\ \ i = [1,\dots,22],\ ts = [1,\dots,16],\ t = [2008,\dots,2030] \qquad (4.18)$$

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[41] The carbon price is termed the Fundamental Carbon Price Indicator (FCPI). For a full explanation on the definition of the FCPI, we refer to Chapter 2.

Here, $FP_{ts,t}^{i}$ is the price of the fuel used by technology i. The prices are denoted in euros per gigajoule energy content (€/GJ). β^{i} is the burn rate of the fuel used by technology i. The burn rate is used to convert the fuel cost from €/GJ into €/MWh. The burn rates thereby specify how much energy a technology uses (in GJ) to produce one MWh of electricity. Two technologies that use the same fuel may have very different burn rates, indicating that one technology is more fuel efficient than the other. The burn rates are exogenous input and are provided in column 5 of Table 9.2.

The fuel prices are generated in the following manner. In general, we allow each fuel price to change after each season s. The fuel prices for the first season of 2008 are exogenous input, and are provided in column 2 of Table 9.4. During a season (covering 4 non-sequential time slices, see Table 9.1) the price indices remain constant. We generate price indices that reflect the historical price pattern of coal, gas, oil and uranium, as well as the correlations between the returns of these four fuels. The fuel price index ($FP_{ts,s,t}^{i}$) related to technology i in season s in year t is defined as:

$$FP_{s,t}^{i} = FP_{s-1,t}^{i} * \left[1 + \mu^{i} + \sigma^{i} W_{s}\right]$$

$$for\ \ i = [1, \dots, 22],\ s = [1, \dots, 4],\ t = [2008, \dots, 2030] \qquad (4.19)$$

Here $FP_{ts,s-1,t}^{i}$ is the price of the fuel used by technology i in the previous season, μ^{i} is the average historical seasonal growth rate of that fuel price and σ^{i} is the associated historical standard deviation. Finally, W_{s} is a standard Wiener process. The standard Wiener process entails that, for each of the four fuels, a value is sampled from a normal distribution with mean 0 and standard deviation 1. The four values are correlated to each other to reflect historically observed correlations between fuel prices. The input values for μ^{i}, σ^{i} and the correlations between fuels are provided in columns 3-9 of Table 9.4. An example of the simulated price path is provided in Figure 9.4. The figure shows the simulated price indices for a single model trail. Figure 9.5 shows the probability distributions of the price indices for 2,000 model trails.

Two fuels, biomass and biogas (see Table 9.4), are not traded on world exchanges. Therefore, historical price data is scarce forcing us to make a simplifying assumption for the price level of these fuels. We assume that biomass and biogas become increasingly popular leading to a fuel price increase of 0.5 percent per season.

Other operating costs (OC^i) - Other operating costs (in €/MWh) are exogenous input to the model. The input values are provided in column 3 of Table 9.3. Other operating costs cover, among others, consumption of water, lubricants, fuel additives, spare parts and repairs. Labour costs are not part of the marginal operating costs but are considered fixed operating costs, since they do not depend on the prevailing production level. Fixed operating costs are accounted for in Section 4.3.2.2.4 on investments.

4.3.2.2.3. Forward Market

The forward market plays an important role for both consumers and producers of electricity. For example, large industrial firms may wish to shield themselves from electricity price uncertainty and buy electricity forward at a pre-determined price. By buying electricity via the forward market, the buyer obtains certainty about the cost of electricity use, while the seller obtains certainty about its minimum production volume. Obtaining certainty about production volumes is beneficial for producers because the conditions on the spot market can change rapidly. For example, in absence of forward contracts, a hike in the gas price may force gas powered generation capacity out of business overnight.

In this study, we want to determine the size and production mix on the forward market for two reasons. First, the production mix on the forward market drives the emission output of the electricity sector. Secondly, the spot market and the forward market are collectively exhaustive. The larger the amount of electricity that is sold via the forward market, the smaller the amount of electricity that is sold via the spot market. This relationship between the spot and forward market was already defined in Equations 4.10 and 4.11, although we did not formalize the parameter $FORP_{ts,t}^{i}$ yet. We will be able to do so at the end of this section, after explaining all elements of the forward market.

Operators are only able to sell their electricity forward if they can offer electricity at a competitive price. We thus have to determine which technologies are expected to be competitive, one and two years ahead. Operators that are forecasted to be competitive are assumed to be willing and able to sell forward contracts. We determine which technologies are competitive by forecasting the one-year-ahead and two-year-ahead economic dispatch procedure on the spot market. The economic dispatch procedure ranks the technologies based on their marginal production cost and can thereby generate forecasts for future production levels.

To determine the spot market for a future period, we have to make some simplifying assumptions because the value of some model parameters is not yet known. Specifically, we have to make assumptions for all of the stochastic parameters in Table 4.1. Regarding fuel prices, we assume that operators are aware of the mean seasonal growth rate of fuel prices (see column 3 of Table 9.4). Second, we also assume that operators know the mean levels for wind power and solar irradiance during each time slice. Third, we assume that operators anticipate that the carbon price remains constant in future periods. Finally, we assume that operators also know the average growth of electricity demand (ELG_t), which we assumed to be 0.5% per year in Section 4.3.2.1. Based on these mean values and mean growth rates, we extrapolate the levels of these input parameters two years ahead.

To determine which technologies are most competitive two years ahead, we run the economic dispatch procedure under the assumed market conditions for that year and solve for $P2_{ts,t}^{i}$:

$minimize$

$$\sum_{i=1}^{22}(MC2_{ts,t}^{i} * P2_{ts,t}^{i}) \qquad for \quad ts = [1,\dots,16],\ t = [2008,\dots,2030] \tag{4.20.1}$$

$subject\ to$

$$0 \leq P2_{ts,t}^{i} \leq CAP_{t+2}^{i} * PF_{ts,t}^{i} \qquad for \quad i = [1,\dots,22],\ ts = [1,\dots,16],\ t = [2008,\dots,2030] \tag{4.20.2}$$

$$\sum_{i=1}^{22} P2_{ts,t}^{i} = D_{ts,t} * (1 + ELG_t)^2 \quad for \quad ts = [1,\dots,16],\ t = [2008,\dots,2030] \tag{4.20.3}$$

Here, $MC2_{ts,t}^{i}$ is the two-year-ahead marginal production cost of technology i (in €/MWh). $MC2_{ts,t}^{i}$ is determined through an extrapolation of the cost parameters in Equation 4.16 over future periods. $P2_{ts,t}^{i}$ is the forecasted two-year-ahead production level of technology i in MWh. Again, two constraints are in place. First, the production level of technology i ($P2_{ts,t}^{i}$) is constrained by a lower bound of zero and an upper bound equal to the two-year-ahead production capacity (in MWh per timeslice). We assume that the retirement scheme and new investments in previous years are known to operators. Investments in year t, $t + 1$ and $t + 2$ are not yet known and therefore cannot be accounted for by operators on the forward market. The second constraint (4.20.3) defines that the total production of all technologies should equal the two-year-ahead demand for electricity in each time slice. Recall that we extrapolate the electricity demand with an annual growth rate of 0.5%.

If the forecasted production level ($P2^{i}_{ts,t}$) is positive, that technology is assumed to be competitive on the forward market. Not all of the forecasted production is sold forward, as only a limited number of consumers is willing to buy electricity two years ahead of delivery. To determine the amount of electricity that is sold two years ahead, we make the following assumption:

$$FOR2^{i}_{ts,t} = 0.1 * P2^{i}_{ts,t} \qquad for \quad i = [1,\dots,22],\ ts = [1,\dots,16],\ t = [2008,\dots,2030] \tag{4.21}$$

We assume that 10% of the forecasted two-year-ahead production level is sold forward.[42] Note that $FOR2^{i}_{ts,t}$ denotes the electricity that is *sold* during time slice ts in year t, but *delivered* during time slice ts in year $t+2$.

We forecast the one-year-ahead electricity market in a similar manner by solving for $P1^{i}_{ts,t}$:

$minimize$

$$\sum_{i=1}^{22}(MC1^{i}_{ts,t} * P1^{i}_{ts,t}) \qquad for \quad ts = [1,\dots,16],\ t = [2008,\dots,2030] \tag{4.22.1}$$

$subject\ to$

$$0 \le P1^{i}_{ts,t} \le CAP^{i}_{t+1} * PF^{i}_{ts,t+1} - FOR2^{i}_{ts,t-1}$$

$$for \quad i = [1,\dots,22],\ ts = [1,\dots,16],\ t = [2008,\dots,2030] \tag{4.22.2}$$

$$\sum_{i=1}^{22} P1^{i}_{ts,t} = D_{ts,t} * (1 + ELG_{t})^{1} - \sum_{i=1}^{22} FOR2^{i}_{ts,t-1}$$

$$for \quad ts = [1,\dots,16],\ t = [2008,\dots,2030] \tag{4.22.3}$$

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[42] Exactly how much electricity is sold forward on the one-year and two-year-ahead basis is lacking. However, we test the sensitivity of this parameter in Section 4.4.5.3, and show the results are very robust to a 50% increase in the size of the forward market.

The amount of electricity that is sold one years ahead is defined as:

$$FOR1_{ts,t}^{i} = 0.4 * P1_{ts,t}^{i} \qquad for \quad i = [1, \dots, 22],\ ts = [1, \dots, 16],\ t = [2008, \dots, 2030] \tag{4.23}$$

Note that there are two key differences compared to the forecast of the two-year-ahead electricity market. First, the total production on the one-year-ahead spot market ($\sum_{i=1}^{22} P1_{ts,t}^{i}$ in Equation 4.22.3) is equal to the demand minus the electricity that was already sold via the two-year-ahead forward market. Secondly, in Equation 4.23, we assume that 40% of the forecasted one-year-ahead production level is sold forward, as opposed to 10% on the two-year-ahead market.

Earlier, in Equation 4.10 and 4.11, we defined $FORP_{ts,t}^{i}$ as the electricity that is sold via the forward market by technology i, and delivered in time slice ts in year t. We are now ready to formalize this parameter:

$$FORP_{ts,t}^{i} = FOR1_{ts,t-1}^{i} + FOR2_{ts,t-2}^{i}$$

$$for \quad i = [1, \dots, 22],\ ts = [1, \dots, 16],\ t = [2008, \dots, 2030] \tag{4.24}$$

$FORP_{ts,t}^{i}$ is denoted in MWh of electricity and is the sum of the electricity that was sold in the previous year $(t - 1)$ on the one-year-ahead market, and the electricity that was sold two years ago $(t - 2)$ on the two-year-ahead market.

4.3.2.2.4. Investments

The future composition of the production mix, and its emission output, depends to a large extent on new investments in generation capacity. The decision to invest in a specific generation technology is made on the basis of its expected profitability. The more profitable a technology is, the more generation capacity is invested in. The investment decision can be summarized in the following equation*:*

$$\mathrm{INV}_t^i = \mathrm{L}^i\left(1 - \mathrm{e}^{-\mathrm{NPV}_t^i/\mathrm{CAPEX}_t^i}\right) \qquad \mathit{for} \quad i = [1, \dots, 22],\ t = [2008, \dots, 2030] \tag{4.25}$$

Equation 4.25 is illustrated in Figure 9.6. The level of investments in technology i (INV_t^i*)* depends on the profitability index of that technology. The profitability index is defined as $\mathrm{NPV}_t^i/\mathrm{CAPEX}_t^i$, where NPV_t^i is the net present value and CAPEX_t^i is the upfront capital expense of investing in a MW of generation capacity.[43] NPV_t^i will be defined later on in this section and input values for CAPEX_t^i are provided in column 5 of Table 9.3. Investments in year t are bounded by a saturation limit (L^i).[44] The assumed input values for L^i are provided in column 8 of Table 9.3. To determine the input values for L^i we took the highest year-to-year increase in generation capacity between 1991 and 2011. To the extent that that rendered improbable results, we manually adjusted the input values.[45] By differentiating the saturation limit between technologies, similar to Olsina *et al.* (2006), we take into account that some technologies are more scalable than others. For technologies without representative historical data, we have assumed values for L^i. Specifically, regarding ocean-based electricity production ($\mathrm{L}^i = 7$ MW), we take into account that the potential to tap tidal, wave and current energy is very low. The technical potential is low because of competing uses of water ways

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[43] Note that the minus sign is not part of the profitability index. The net present value is calculated based on a required rate of return of 6%. If the net present value is positive, it indicates that the expected return surpasses 6%, which leads to investments.

[44] For high levels of profitability is seems logical to assume a saturation level for new investments. First, operators may anticipate the mass entry of new generation capacity. New entrants thereby saturate the market and reduce the profitability of existing production capacity and additional new investments. Secondly, banks may only be willing to simultaneously fund a limited number of new investment projects (Olsina *et al., 2006*).

[45] For some technologies, insufficient historical data is available. For others, the historical data provided odd results. For example, based on the historical data method, the saturation limit for nuclear power should be 267 MW. For comparison, a single typical plant within the current portfolio already produces approximately 1,400 MW. Therefore, we have set the saturation limit somewhat higher to 1,000 MW.

and concerns over nature conservation (Bömer *et al.*, 2010). For geothermal technology ($\mathrm{L}^{\mathrm{i}} = 750\ \mathrm{MW}$), we assume a relatively low saturation limit because its technical potential is almost exclusively located in the north of Germany (Schulz *et al.*, 2007). Also, the long exploration process that is required to find locations with optimal geological conditions (Stafánsson, 2002) limits the scalability of the technology. Finally, the saturation limits for technologies with CCS (*e.g.* Black Coal with CCS) are assumed to be 50% of the saturation limit of the same technology without CCS (Black Coal). Thereby, we account for the fact that CCS technology has high infrastructural requirements including a CO_2 storage location. The remainder of Section 4.3.2.2.4 is devoted to an explanation of the manner in which the net present value is calculated.

Net Present Value calculation - To calculate the net present value of a technology, we discount the expected cash flows. Again, we use the subscript ya to denote cash flows that lie ya years into the future. The subscript ya ranges from $\mathrm{CT}^{\mathrm{i}} + 1$ (the first operational year after the construction time) to $\mathrm{CT}^{\mathrm{i}} + \mathrm{LT}^{\mathrm{i}}$ (the investment horizon). The net present value ($\mathrm{NPV}_{\mathrm{t}}^{\mathrm{i}}$) of technology i in year t is denoted in €/MW and is defined as:

$$\mathrm{NPV}_{\mathrm{t}}^{\mathrm{i}} = -\mathrm{CAPEX}_{\mathrm{t}}^{\mathrm{i}} + \sum_{\mathrm{ya}=CT^{i}+1}^{\mathrm{CT}^{\mathrm{i}}+\mathrm{LT}^{\mathrm{i}}} \frac{\sum_{\mathrm{ts}=1}^{16}(\mathrm{RF}_{\mathrm{ts,t,ya}}^{\mathrm{i}} - \mathrm{CF}_{\mathrm{ts,t,ya}}^{\mathrm{i}})}{(1+\mathrm{r})^{\mathrm{ya}}}\ for\ i = [1, \dots, 22], t = [2008, \dots, 2030] \quad (4.26)$$

$$if \quad \mathrm{RF}_{\mathrm{ts,t,ya}}^{\mathrm{i}} - \mathrm{CF}_{\mathrm{ts,t,ya}}^{\mathrm{i}} < 0 \quad \text{then} \quad \mathrm{RF}_{\mathrm{ts,t,ya}}^{\mathrm{i}} - \mathrm{CF}_{\mathrm{ts,t,ya}}^{\mathrm{i}} = -\mathrm{FOC}_{\mathrm{t}}^{\mathrm{i}} * 1.01^{ya} \quad (4.27)$$

Here, $\mathrm{RF}_{\mathrm{ts,t,ya}}^{\mathrm{i}}$ is the forecasted revenue and $\mathrm{CF}_{\mathrm{ts,t,ya}}^{\mathrm{i}}$ is the forecasted cost in time slice ts, ya years ahead of t. The expected cash flow is discounted with a discount rate (r) of 6%. Note from Equation 4.27 that, if the forecasted cash flow ya years ahead is negative, we assume that the forecasted cash flow is equal to the fixed operating costs of technology i

(FOC^i, denoted in *€/MW*). We make this assumption, because we assume that an operator will not produce electricity if the expected payoff is negative. The only costs that are incurred if the operator does not produce electricity are the fixed operating costs, which include employee wages and planned maintenance. Input values for the fixed operating costs are provided in column 4 of Table 9.3. The fixed operating costs are assumed to grow annually with 1%. In the remainder of this section, we will define the parameters $\mathrm{RF}^{\mathrm{i}}_{\mathrm{ts,t,ya}}$ and $\mathrm{CF}^{\mathrm{i}}_{\mathrm{ts,t,ya}}$.

Forecasted revenue ($\mathrm{RF}^{\mathrm{i}}_{\mathrm{ts,ya}}$*)* - The forecasted revenue ($\mathrm{RF}^{\mathrm{i}}_{\mathrm{ts,ya}}$) per MW is defined as:

$$\mathrm{RF}^{\mathrm{i}}_{\mathrm{ts,t,ya}} = EF_{ts,t,ya} * EPF^{i}_{ts,t}$$

$$for\ i = [1, \dots, 22],\ ts = [1, \dots, 16],\ t = [2008, \dots, 2030],\ ya = \{CT^i + 1, \dots, \mathrm{CT^i} + \mathrm{LT^i}\} \qquad (4.28)$$

Here, $EF_{ts,t,ya}$ is the forecast of the electricity price (in €/MWh) and $EPF^{i}_{ts,t,ya}$ is the expected production factor (in MWh/MW) in time slice ts, ya years ahead of t. The forecast of the electricity price that is made during time slice ts in year t, ya years into the future, is defined as:

$$EF_{ts,t,ya} = E_{ts,t} + \frac{ya}{2}\left(\max_{i}\left(MC2^{i}_{ts,t} \middle| P2^{i}_{ts,t} > 0\right) - E_{ts,t}\right)$$

$$for\ ts = [1, \dots, 16],\ t = [2008, \dots, 2030],\ ya = [1, \dots, 54] \qquad (4.29)$$

We calculate the ya-year ahead forecast of the electricity price through linear extrapolation of the spot electricity price ($E_{ts,t}$) and the two-year ahead electricity price

$(\max_i(MC2^i_{ts,t} | P2^i_{ts,t} > 0))$.[46]

The expected production factor $EPF^i_{ts,t}$ (in MWh/MW) of technology i in future periods is defined as:

$$EPF^i_{ts,t} = \left(\sum_{\tau=t-2}^{t} \frac{P^i_{ts,\tau} + FORP^i_{ts,\tau}}{CAP^i_t}\right)/3 \qquad for\ i = [1,\ldots,22],\ ts = [1,\ldots,16],\ t = [2008,\ldots,2030] \qquad (4.30)$$

The forecasted production factor is equal to the average production level over the previous three years (in MWh), divided by the installed generation capacity (in MW). The expected production factor is assumed to be the same for all time slices and years in the investment horizon.[47]

Forecasted cost ($\mathrm{CF}^{\mathrm{i}}_{\mathrm{ts,ya}}$*)* - The forecasted production costs (in €/MW) for technology i, ya years ahead, are defined as:

$$\mathrm{CF}^{\mathrm{i}}_{\mathrm{ts,t,ya}} = EPF^i_{ts,t}\left[EC^i_t + FC^i_{ts,t}(1+\mu^i)^{ya*4} + OC^i * 1.01^{ya}\right] + FOC^i * 1.01^{ya}$$

$$for\ i = [1,\ldots,22],\ ts = [1,\ldots,16],\ t = [2008,\ldots,2030],\ ya = \{CT^i + 1,\ldots,\mathrm{CT^i + LT^i}\} \qquad (4.31)$$

The costs depend on the expected production factor ($EPF^i_{ts,t}$), the forecasted marginal operating costs (the terms in between square brackets) and the fixed operating expenses (FOC^i). Note that the marginal operating expenses are similarly defined as in Equation 4.16, although we now take an annual growth factor into account. The carbon price is assumed to remain constant. Fuel prices increase with the assumed mean seasonal growth rate. Other

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[46] We forecast a maximum of 54 years ahead ($ya = [1,\ldots,54]$) because hydropower is the technology with the longest investment horizon (4 years of construction and 50 years of operational lifetime, see Table 9.2).

[47] Note that the expected production factor is a forecast based on realized production levels, while we calculated the maximum production factor in Equation 4.5.

operating expenses (OC^i) and fixed operating expenses (FOC^i) are assumed to increase by 1% annually.

4.3.2.3. NPO & FITS

In the previous sections we have laid out all of the components of the GPSM assuming that no other instruments are in place except for the EU ETS. Therefore, we will now describe how the above algorithm is impacted once we allow for the NPO and FITs.

NPO - The impact of the NPO is relatively straight-forward. The existing nuclear generation capacity ($CAP_t^{i=17}$) is phased out along the timetable set out in Table 9.5 in the Appendix. After 2022, nuclear power is completely phased out. Obviously, apart from phasing out existing generation capacity, the NPO also implies that no new investments are allowed ($INV_t^{i=17} = 0$).

FITs - FITs change the modelling algorithm via three characteristics that distinguish FIT-capacity from regular generation capacity: (1) the FITs change the NPV of each technology, and thereby changes investment behaviour, (2) FIT-capacity has guaranteed access to the grid, thereby operators no longer rely the spot and forward market, and (3) the FIT scheme is paid for via a mark-up on the retail electricity price (known as the EEG apportionment). How each of the three characteristics impacts the GPSM will be explained below.

Characteristic 1: The effect of FITs on investments – Because operators of FIT-capacity receive a FIT that is generally higher than the electricity price on the spot or forward market, their expected revenue increases. This stimulates investments in FIT-capacity, and provides downward pressure on the CO_2 emission output of the sector. The FIT that operators receive depends on the year in which FIT-capacity becomes operational. However, once the FIT-capacity has become operational (and the FIT has been set), the FIT remains fixed over the first 20-years of its operational lifetime.

The forecasted revenue of FIT-capacity of technology i (in €/MW), ya years ahead, is defined as:

$$\mathrm{RFFIT}^{\mathrm{i}}_{\mathrm{ts,t,ya}} = \left(\epsilon^{\mathrm{i}}_{\mathrm{ya}}\mathrm{FIT}^{\mathrm{i}}_{t+CT+1^i} + (1-\epsilon^{\mathrm{i}}_{\mathrm{ya}})EF_{ts,t,ya}\right)FITEPF^i_{ts,t}$$

$$for\ i = [1,\ldots,22],\ ts = [1,\ldots,16],\ t = [2008,\ldots,2030],\ ya = \{CT^i+1,\ldots,\mathrm{CT^i}+\mathrm{LT^i}\} \qquad (4.32)$$

Equation 4.32 is an extension of Equation 4.28. $\mathrm{FIT}^{\mathrm{i}}_{t+CT^i+1}$ is the FIT (in €/MWh) that is applicable to capacity of technology i that becomes operational in year $\mathrm{t} + CT^i + 1$. FIT-tariffs are taken from the German Erneuerbare-Energien-Gesetz (Bundestag, 2004, 2009, 2012). $FITEPF^i_{ts,ya}$ is the realized production factor of FIT-capacity over the past 3 years (analogous to 4.30). $\epsilon^{\mathrm{i}}_{\mathrm{ya}}$ is a dummy:

$$\epsilon^{\mathrm{i}}_{\mathrm{ya}} = 1 \quad if\ ya = \{CT^i+1,\ldots,CT^i+20\} \qquad for\ i = [1,\ldots,22] \qquad (4.33.1)$$

$$\epsilon^{\mathrm{i}}_{\mathrm{ya}} = 0 \quad if\ ya = \{CT^i+21,\ldots,CT^i+LT^i\} \qquad for\ i = [1,\ldots,22] \qquad (4.33.2)$$

The dummy parameters account for the fact that, after 20 operational years, operators of technology i no longer receive the FIT-tariff, but receive the spot electricity price instead.

By replacing $\mathrm{RF}^{\mathrm{i}}_{\mathrm{ts,t,ya}}$ with $\mathrm{RFFIT}^{\mathrm{i}}_{\mathrm{ts,t,ya}}$ and $EPF^i_{ts,t,ya}$ with $FITEPF^i_{ts,t,ya}$ we calculate the net present value of FIT-capacity ($\mathrm{NPVFIT}^{\mathrm{i}}_{\mathrm{t}}$), instead of regular capacity ($\mathrm{NPV}^{\mathrm{i}}_{\mathrm{t}}$ in Equation 4.26).

$$if\ \ \mathrm{NPVFIT}^{\mathrm{i}}_{\mathrm{t}} \geq \mathrm{NPV}^{\mathrm{i}}_{\mathrm{t}} \quad \varrho^i_t = 1 \qquad for\ i = [1,\ldots,22],\ t = [2008,\ldots,2030] \qquad (4.34.1)$$

$$if\ \ \mathrm{NPVFIT}_t^i < \mathrm{NPV}_t^i \quad \varrho_t^i = 0 \qquad for\ i = [1, \dots, 22],\ t = [2008, \dots, 2030] \tag{4.34.2}$$

We assume that investors in technology i opt to receive the FIT-tariff if the net present value of FIT-capacity (NPVFIT_t^i) is greater than the net present value of regular capacity (NPV_t^i). Conversely, if the net present value of regular capacity is greater than the net present value of FIT-capacity, we assume that operators opt to invest in regular capacity (and forgo the option to participate in the FIT-scheme). The dummy variable ϱ_t^i indicates whether investments in technology i in year t represent FIT-capacity ($\varrho_t^i = 1$) or regular capacity ($\varrho_t^i = 0$). This dummy will be used below.

Characteristic 2: Priority Dispatch – Priority dispatch implies that operators of FIT-capacity have guaranteed access to the grid and therefore are no longer dependent on the spot or forward market to sell electricity. Any electricity that is produced can be sold against the pre-determined FIT-tariff. Therefore, if the FIT-tariff is greater than the marginal production costs, we assume that operators of FIT-capacity produce at maximum capacity. The production level (in MWh) of all FIT-capacity of technology i in slice ts in year t is:

$$FITP_{ts,t}^i = \sum_{d=CT^i+1}^{CT^i+1+t} \left(INV_{t-d}^i \varrho_{t-d}^i \varpi_{t-d}^i PF_{ts,t}^i \right)$$

$$for\ \ i = [1, \dots, 22],\ ts = [1, \dots, 16],\ t = [2008, \dots, 2030] \tag{4.35}$$

We distinguish between (and sum over) all previous years in the simulation because the profitability of generation capacity depends on the FIT that applied in the year in which the generation capacity first becomes operational. $INV_{t-(CT^i+1)}^i$ represents the newest generation capacity of technology i, as it becomes operational in year t. $INV_{t-(CT^i+1+t)}^i$ represents the generation capacity that became operational in 2008, the first year of the simulation. For 2008, we use exogenous input that is provided in columns 9 and 10 of Table

9.3. The input data captures all FIT-based capacity that was deployed by 2008, since the introduction of FITs in Germany. Finally, ϖ is a dummy that indicates whether producing electricity is profitable during time slice ts in year t for FIT-capacity that was invested in in year $t-d$:

$$if\ MC^{i}_{ts,t} < \mathrm{FIT}^{\mathrm{i}}_{\mathrm{t-d}+CT^{i}+1} \quad \varpi^{i}_{t-d} = 1$$

$$for\ \ i = [1,\dots,22],\ ts = [1,\dots,16],\ t = [2008,\dots,2030],\ d = [CT^{i}+1,\dots,CT^{i}+1+t] \qquad (4.36.1)$$

$$if\ MC^{i}_{ts,t} \geq \mathrm{FIT}^{\mathrm{i}}_{\mathrm{t-d}+CT^{i}+1} \quad \varpi^{i}_{t-d} = 0$$

$$for\ \ i = [1,\dots,22],\ ts = [1,\dots,16],\ t = [2008,\dots,2030],\ d = [CT^{i}+1,\dots,CT^{i}+1+t] \qquad (4.36.2)$$

If the marginal production costs of technology i are lower than the applicable FIT-tariff[48] the operators can make a profit by producing, and hence ϖ^{i}_{t-d} is equal to one. If the marginal production costs are equal or higher than the applicable FIT-tariff the operator is not able to make a profit, and hence ϖ^{i}_{t-d} is equal to zero.

The production of electricity by FIT-capacity affects the spot market: the greater the production level of FIT-capacity (Equation 4.35), the smaller the production via the spot market. We rewrite Equations 4.10 to account for this:

$$SD_{ts,t} = D_{ts,t} - \sum_{i=1}^{22} FORP^{i}_{ts,t} - \sum_{i=1}^{22} FITP^{i}_{ts,t} \qquad for\ \ ts = [1,\dots,16],\ t = [2008,\dots,2030] \qquad (4.37)$$

The demand on the spot market is lower, because part of the demand for electricity is fulfilled by FIT-capacity ($\sum_{i=1}^{22} FITP^{i}_{ts,t}$). Similarly, we rewrite Equation 4.11:

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[48] Investments from year $t-d$ become operational in year $\mathrm{t-d}+CT^{i}+1$. Hence, the applicable FIT-tariff of INV^{i}_{t-d} is $\mathrm{FIT}^{\mathrm{i}}_{\mathrm{t-d}+CT^{i}+1}$.

$$SP_{ts,t}^{i} = \left(CAP_{t}^{i} - \sum_{d=CT^{i}+1}^{CT^{i}+1+t} \left(INV_{t-d}^{i} ϙ_{t-d}^{i} \varpi_{t-d}^{i} \right) \right) * PF_{ts,t}^{i} - FORP_{ts,t}^{i}$$

$$for \quad i = [1, \dots ,22],\ ts = [1, \dots ,16],\ t = [2008, \dots ,2030] \tag{4.38}$$

The maximum production limit of technology i (in MWh) that is available on the spot market decreases because part of the production capacity is FIT-capacity.

Similarly, the one-year and two-year ahead spot market are affected. Therefore, we rewrite Equations 4.20.2, 4.20.3, 4.22.2 and 4.22.3 to account for lower demand levels and production limits on forward markets:

$$0 \le P2_{ts,t}^{i} \le CAP_{t+2}^{i} * PF_{ts,t}^{i} - FITP_{ts,t+2}^{i}$$

$$for \quad i = [1, \dots ,22],\ ts = [1, \dots ,16],\ t = [2008, \dots ,2030] \tag{4.39}$$

$$\sum_{i=1}^{22} P2_{ts,t}^{i} = D_{ts,t} * (1 + ELG_{t})^{2} - \sum_{i=1}^{22} FITP_{ts,t+2}^{i}$$

$$for \quad i = [1, \dots ,22],\ ts = [1, \dots ,16],\ t = [2008, \dots ,2030] \tag{4.40}$$

$$0 \le P1_{ts,t}^{i} \le CAP_{t+1}^{i} * PF_{ts,t}^{i} - FITP_{ts,t+1}^{i}$$

$$for \quad i = [1, \dots ,22],\ ts = [1, \dots ,16],\ t = [2008, \dots ,2030] \tag{4.41}$$

$$\sum_{i=1}^{22} P1_{ts,t}^{i} = D_{ts,t} * (1 + ELG_{t}) - \sum_{i=1}^{22} FOR2_{ts,t-1}^{i} - \sum_{i=1}^{22} FITP_{ts,t+1}^{i}$$

$$for \quad ts = [1, \dots ,16],\ t = [2008, \dots ,2030] \tag{4.42}$$

Finally, we have to account for the emissions from FIT-based production capacity. Equation 4.14 therefore becomes:

$$EM_{t} = \sum_{i=1}^{22} \left[\sum_{ts=1}^{16} \left(P_{ts,t}^{i} + FORP_{ts,t}^{i} + FITP_{ts,t}^{i} \right) CI^{i} \right] / 1{,}000{,}000$$

$$for\ t = [2008, \dots ,2030] \tag{4.43}$$

Characteristic 3: the EEG apportionment – The EEG apportionment is a mark-up on the retail electricity price to finance the FIT-scheme. Network operators are responsible for the financing of the FIT-scheme. Network operators buy electricity from operators of FIT-capacity against the going FIT-tariff and sell the electricity to consumers against the going spot price. The network operators settle the difference by charging consumers via the EEG apportionment. The EEG apportionment (in €/MWh) is thus added to Equation 4.2 that defines the retail electricity price:

$$RE_t = \frac{\left(\sum_{ts=1}^{22} E_{ts,t} SD_{ts,t}\right)}{\sum_{ts=1}^{22} SD_{ts,t}} + EEG_t + 140 \qquad for\ t = [2008, \dots, 2030] \tag{4.44}$$

The level of the EEG apportionment is calculated as follows:

$$EEG_t = \frac{FITEXP_t - FITREV_t}{TDEEG_t} \qquad for\ t = [2008, \dots, 2030] \tag{4.45}$$

Here, EEG_t is the EEG apportionment in €/MWh in year t. $FITEXP_t$ represents the expenses of network operators (in €) to finance the FIT-scheme. $FITREV_t$ represents the revenues (in €) that are obtained by network operators by selling the FIT-based electricity. Finally, $TDEEG_t$ represents the total demand by consumers that are obliged to pay the EEG apportionment. $TDEEG_t$ is lower than TD_t (total demand, Equation 4.1) because some consumers are exempt from paying the EEG apportionment:

$$TDEEG_t = TD_t - Down_t - Dpriv_t - Dexp_t - Dloss_t \qquad for\ t = [2008, \dots, 2030] \tag{4.46}$$

Here, TD_t represents the total demand for electricity. We differentiate between four types of electricity consumption that are exempt from paying the EEG apportionment. $Down_t$

represents the electricity use by the electricity sector itself. $Dpriv_t$ represents so-called privileged demand which includes sectors that face strong international competition, $Dexp_t$ represents the exports of electricity and $Dloss_t$ represents the network losses and unregistered usage of electricity. The assumed input values and sources for these parameters can be found in Table 9.6.

$$FITEXP_t = \sum_{i=1}^{22}\left[\sum_{d=CT^i+1}^{t}\left(INV_{t-d}^{i}\text{ϙ}_{t-d}^{i}\varpi_{t-d}^{i}PF_{ts,t}^{i} * \mathrm{FIT}_{\mathrm{t-d}+CT^i+1}^{\mathrm{i}}\right)\right]$$
$$for\ t = [2008, \dots, 2030] \qquad (4.47)$$

The FIT expenses are calculated by multiplying the production level (as obtained via Equation 4.35) with the applicable FIT-tariff and summing over all technologies.

$$FITREV_t = \sum_{ts=1}^{16}\left(FITP_{ts,t}^{i} * E_{ts,t}\right) \qquad for\ t = [2008, \dots, 2030] \qquad (4.48)$$

The revenues are obtained by multiplying the FIT-based production level with the spot electricity price in each time slice and summing over all time slices.

4.3.2.4. INTEGRATION WITH THE ETSM

For a detailed description of the ETSM, we refer to Chapter 2. Here, we highlight the adjustments that have been made to integrate the GPSM with the ETSM.

First, the demand for EU ETS emission allowances is specified as:

$$AD_t = (AD_{t-1} - EM_{t-1})(1 + EG_t) + EM_t - T1_t - T2_t \qquad for\ t = [2008, \dots, 2030] \qquad (4.49)$$

Equation 4.49 is the adjusted form of Equation 3.4 in Chapter 3. The emissions from the German power sector (EM_t) are now included as a separate term and are no longer directly driven by the stochastically sampled emissions growth rate in the rest of Europe (EG_t). AD_{t-1} represents total demand for emission allowances in the previous year.[49] EG_t is the stochastically sampled emissions growth rate. EG_t is sampled from a distribution with a mean of 0.33% and a standard deviation of 2.08%.[50] The parameters $T1_t$ and $T2_t$ capture the impact of parallel instruments in other sectors of the EU ETS (other than the German power sector). $T1_t$ and $T2_t$ will be further explained below.

Note that both EG_t (Equation 4.49 in the ETSM) and ELG_t (Equation 4.1 in the GPSM) are intrinsically linked to the level of economic growth in the EU. If the economy in the EU stagnates, the CO_2 emissions in the rest of the EU (EG_t), as well as the demand for electricity in Germany (ELG_t) are expected to fall. Conversely, if the economy in Europe grows, both the emission level in the rest of the EU and the demand for electricity in Germany are expected to rise. To account for this, EG_t and ELG_t are sampled with a correlation of 0.54. The correlation was calculated over the interval 1994-2008, based on emission data from the EEA (2012) and German electricity demand figures from AGEB (2013a).

Apart from FITs and the NPO, there are many more operational parallel instruments in Europe today that influence the CO_2 emission level. To account for these other parallel instruments, $T1_t$ and $T2_t$ are included in Equation 4.49. These other parallel instruments are not modelled in detail, but instead we account for them by assuming an aggregate effect on the emission level in EU ETS sectors (*e.g.* we assume in Section 4.4.4 that other parallel instruments trigger abatement activity of 10 $MtCO_2$ per annum). We distinguish between two

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[49] In Chapter 2, AD_{t-1} is the sum of several sources of demand. For clarity, we have left these other parameters out of the description here. For a full description, see section 2.2.3.

[50] To represent the impact of the recession that started in 2008, the input values for EG_t over the period 2008-2012 have been set deterministically based on historical data, similar to ELG_t in Equation 4.1.

types of parallel instruments ($T1_t$ and $T2_t$) because they have a different impact on the performance of the EU ETS. Type 1 instruments ($T1_t$) are defined as instruments that lower the *carbon intensity* of production in ETS-sectors (*e.g.* by triggering investments in more efficient production technologies in the electricity sector). Type 2 instruments ($T2_t$) are defined as instruments that reduce the *production levels* in ETS-sectors (*e.g.* by triggering the deployment of decentralized solar power). For a full explanation of the difference between Type 1 and Type 2 instruments and more examples of both types of instruments that are currently in place in the EU, we refer to Chapter 3.

Note that the key model parameters to which we will refer in the results section are the following three: the emission level in the German power sector (Equation 4.14, or 4.43), the emission level under the EU ETS as a whole (Equation 4.49) and the FCPI (Equations 2.7.1 and 2.7.2).

4.3.3. Scenarios

The eight scenarios that will be tested are outlined in Table 4.2. Scenario 1 is a scenario without any instruments in place from 2008 to 2030. We test three scenarios with a single instrument (Scenarios 2, 3 and 4), three scenarios with a combination of two instruments (Scenarios 5, 6 and 7) and one scenario with all three instruments (Scenario 8).

Table 4.2: 8 Scenarios

Instruments / Scenarios	**1** **No Instruments**	**2** **EU ETS only**	**3** **FIT only**	**4** **NPO**	**5** **EU ETS + FIT**	**6** **FIT + NPO**	**7** **EU ETS + NPO**	**8** **All instruments**
EU ETS		✓			✓		✓	✓
FIT			✓		✓	✓		✓
NPO				✓		✓	✓	✓

In the first set of simulations, we do not consider the potential effect of parallel instruments in sectors other than the German power sector. We do account for additional parallel instruments in Section 4.4.4. We re-run all scenarios assuming the aggregate impact of both Type 1 ($T1_t$) and Type 2 ($T2_t$) instruments on the emission level under the EU ETS is -5 $MtCO_2$/yr, leading to a total aggregate effect of parallel instruments of -10 $MtCO_2$/yr.

Because, to our knowledge, empirical data on the relative influence of Type 1 and Type 2 instruments is not available, we assume that Type 1 and Type 2 instruments have an equally strong influence on the emission level (-5 $MtCO_2$/yr). The rationale for the total impact of Type 1 and Type 2 instruments (-10 $MtCO_2$/yr) will be explained at the start of Section 4.4.4, because it is based on the results in Table 4.3 in the next section. For purposes of clarity we refer to all parallel instruments that are operational outside the German power sector as External Instruments (EIs) in the remainder of this study and make no further analytical distinction between Type 1 and Type 2 instruments. For a detailed analysis of the different impact of Type 1 versus Type 2 instruments on the EU ETS, see Chapter 3.

4.4. Results

The mean value, the 10th percentile and the 90th percentile of each output parameter are shown in Table 4.3. Mean values for the carbon price and emission level are also displayed in Figures 4.3 and 4.4. For easy referencing, each column and row is numbered. The numbering is provided in the first column and the first row of Table 4.3. For example, the 2030 mean carbon price under Scenario 2 is provided in column 7, row 6. Quick references are provided in the text in the following format: (column 7, row 6). Due to rounding, values may not add up exactly.

Table 4.3: Carbon price, emission level and abatement per year (10th perc/mean/90th perc)

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	**Output Parameter / Scenario**		**1** **No Instruments**			**2** **EU ETS**			**3** **FITs**			**4** **NPO**			**5** **EU ETS + FIT**			**6** **FIT + NPO**			**7** **EU ETS + NPO**			**8** **All Instruments**		
2			P10	**M**	P90	P10	**M**	P90	P10	**M**	P90	P10	**M**	P90	P10	**M**	P90	P10	**M**	P90	P10	**M**	P90	P10	**M**	P90
3	**Carbon price €/tCO$_2$**	2015				0	**0**	0							0	**0**	0				0	**2**	0	0	**0**	0
4		2020				10	**32**	46							0	**19**	40				23	**37**	55	0	**24**	40
5		2025				27	**49**	66							9	**36**	65				35	**55**	66	20	**44**	66
6		2030				19	**40**	50							17	**35**	50				17	**40**	50	17	***35***	50
7		2030 Diff.				Reference									€-5 -13%						€-0 -1%			€-5 -14%		
8	**Emissions in German power sector in MtCO$_2$**	2015	284	**311**	329	280	**309**	327	217	**242**	261	329	**354**	369	213	**239**	258	264	**291**	309	323	**352**	369	262	**289**	307
9		2020	310	**352**	382	283	**331**	366	220	**254**	279	340	**392**	423	203	**243**	269	259	**294**	319	302	**364**	406	236	**280**	307
10		2025	349	**398**	438	288	**350**	399	253	**293**	324	382	**440**	484	218	**267**	302	287	**329**	363	307	**377**	435	239	**294**	335
11		2030	357	**423**	479	255	**329**	388	262	**314**	356	387	**459**	513	187	**253**	303	290	**337**	378	279	**354**	415	209	**273**	323
12		2030 Diff.	+94 Mt +29%			Reference			-15 Mt -5%			+130 Mt +40%			-76 Mt -23%			+8 Mt +2%			+25 Mt +8%			-56 Mt -17%		
13	**All Emissions under EU ETS**	Mean in 2030	**1,886 Mt**			**1,548 Mt**			**1,777 Mt**			**1,922 Mt**			**1,541 Mt**			**1,800 Mt**			**1,545 Mt**			**1,538 Mt**		
14		Diff.	+338 Mt +22%			Reference			+229 Mt +15%			+374 Mt +24%			-7 Mt -0 %			+252 Mt +16%			-3 Mt -0%			-10 Mt -1 %		
15	**Abatement per year in Ger. power sector in MtCO$_2$**	**’08-‘30**	+2	**+5**	+7	-3	**+1**	+4	-3	**0**	+2	+3	**+6**	+9	-6	**-3**	0	-1	**+1**	+2	-1	**+2**	+5	-5	**-2**	+1
16		‘08-‘15	-6	**-2**	+1	-4	**0**	+2	-15	**-11**	-9	+1	**+4**	+7	-14	**-10**	-8	-8	**-5**	-2	+2	**+6**	+8	-7	**-3**	-1
17		‘16-‘20	0	**+8**	+14	-5	**+4**	+11	-4	**+2**	+7	-3	**+8**	+14	-7	**+1**	+6	-6	**+1**	+6	-10	**+2**	+11	-11	**-2**	+4
18		‘21-‘25	-1	**+9**	+17	-9	**+4**	+14	0	**+8**	+14	-2	**+10**	+19	-5	**+5**	+12	-1	**+7**	+14	-11	**+3**	+14	-8	**+3**	+11
19		‘26-‘30	-8	**+5**	+16	-19	**-4**	+8	-6	**+4**	+13	-11	**+4**	+15	-16	**-3**	+7	-8	**+2**	+10	-20	**-5**	+8	-17	**-4**	+6

4.4.1. No instruments (Scenario 1)

Without any instruments in place, the emission level increases with an average of 5 MtCO$_2$ per year (column 4, row 15), to 423 MtCO$_2$ in 2030 (column 4, row 11). Note that the growth in emissions varies over time. Over the interval 2008-2015, the emissions change by an average of -2 MtCO$_2$ per year (column 4, row 16), while the emissions increase by an

Figure 4.2: Sources of uncertainty around 2030 emission level

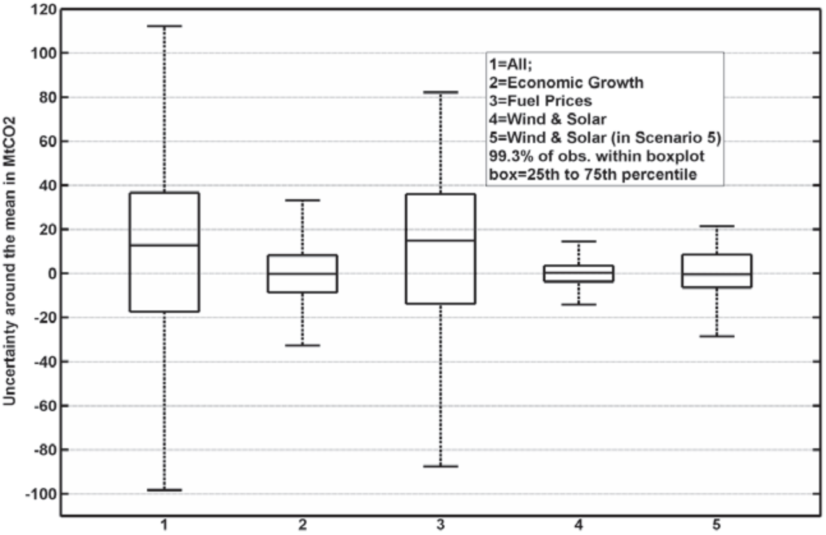


Figure 4.3: Mean Carbon price

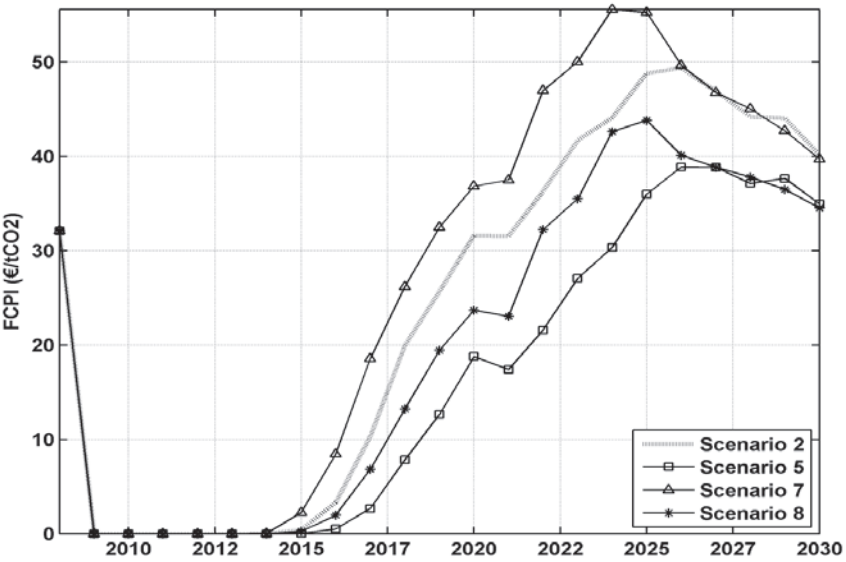


Figure 4.4: Mean emission level

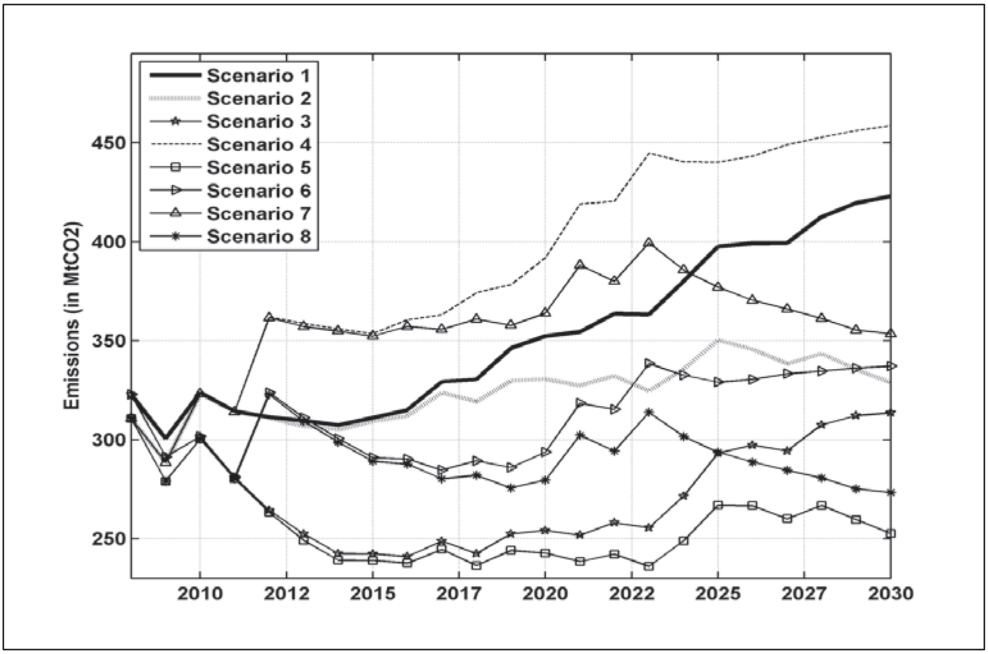
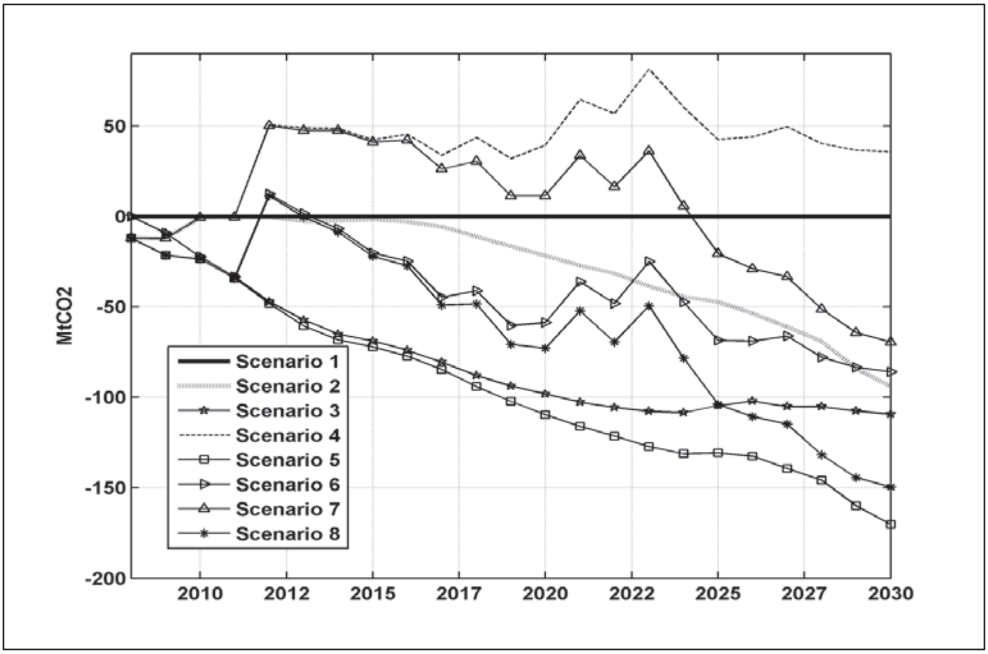


Figure 4.5: Impact of instrument(s) over time compared to Scenario 1 (without instruments)



average of 9 $MtCO_2$ per year over the interval 2021-2025 (column 4, row 18). Without any instruments in place, the emission level in all sectors that would normally fall under the EU ETS increases to 1,886 $MtCO_2$ (column 4, row 13).

Note that the confidence intervals around the means are generated because several model parameters are modelled stochastically. To show which stochastic parameters are most responsible for uncertainty around the means, we refer to Figure 4.2. The figure shows all sources of uncertainty around the mean emission level in 2030 for Scenario 1 (column 4, row 11). The mean levels are normalized to zero, the median is indicated by the horizontal line close to the middle of each box, the edges of the boxes indicate the 25th to the 75th percentile and finally the whiskers indicate approximately 99.3% of all observations. Boxplot 1 combines all stochastic parameters, and relates directly to the results of Scenarios 1 in Table 4.3. Boxplots 2, 3, 4 and 5 capture one (or two in boxplot 4 and 5) classes of stochastic uncertainty (the other classes are controlled for by assuming mean values). Fuel price uncertainty is the biggest driver of uncertainty in the future emission level, followed by uncertainty in the business-as-usual emission growth rate. The latter driver is, at least partly, dependent on the economic growth rate. Finally, uncertain irradiation levels and wind speeds are a relatively small source of uncertainty regarding the 2030 emission level. Boxplot 5 shows that the uncertainty stemming from the supply of wind and solar power does become significantly larger if intermittent technologies play a more important role in the portfolio of electricity supply. Boxplot 5 was obtained from Scenario 5 (EU ETS + FITs).

4.4.2. Scenarios with one instrument (Scenarios 2 to 4)

The introduction of the EU ETS (Scenario 2) leads to a 94 $MtCO_2$ fall in the 2030 emission level compared to Scenario 1 (column 4, row 12). Before 2025, a surplus of emission allowances results in a low carbon price and limited abatement activity. Between 2026 and 2030, emissions fall by an average of -4 $MtCO_2$ per year (column 7, row 19). The average FCPI peaks at €49 in 2025 (column 7, row 5). Note that we refer to Scenario 2 as the reference scenario in Table 4.3 (see *e.g.* column 7, row 12) because we are mainly interested in the effect of introducing instruments alongside the EU ETS.

Figure 4 shows that the FITs (Scenario 3) lead to a sharper fall in emissions than the EU ETS (Scenario 2) until 2030. FITs lead to an emission level of 314 $MtCO_2$ (column 10, row 11) and most of the abatement that is triggered by FITs is achieved before 2015 (column 10, row 16). FITs are more effective in early years of the simulation because the German government has set FIT-tariffs that fall each year. Thereby, the incentive from FITs becomes weaker as time progresses. The slowdown may be less pronounced if a higher rate of technological learning is assumed (so far 0%). In the sensitivity analysis (see Section 4.4.5), we analyse the effect of technological learning in more detail.

Finally, Scenario 4, with an NPO as the sole instrument, leads to the highest expected emission level: the 2030 emission level is expected to be 130 $MtCO_2$ higher than the emission level found in Scenario 2 (column 13, row 12). Despite this overall increase, the year-to-year growth in the emission level is slightly lower over the interval 2025-2030 if an NPO is in place compared to Scenario 1 (comparing column 4, row 19 and column 13, row 19). This result can be explained by the fact that much of the nuclear generation capacity would be retired anyway in these last five years of the simulation window. The NPO leads to a gradual retirement of nuclear capacity before 2022, often only a few years before that capacity would have been retired anyway. As a result, without a NPO in place, the energy sector has to absorb the retirement of nuclear generation capacity generation a few years later, providing upward pressure to the emission level in those years.

4.4.3. Scenarios with multiple instruments (Scenarios 5 to 8)

Because FITs trigger the most CO_2 abatement activity in early years, while the EU ETS is the most effective in later years, Scenario 5 results in a relatively constant abatement tempo over time (see Figure 4.5) and the lowest projected emission level in Germany in 2030.

However, the results also show that the emission level in Europe as a whole remains unchanged in Scenario 5 (-0%, column 16, row 14). Scenarios 7 and 8 also include an EU ETS and show that FITs and the NPO do not affect the overall emission level in the EU. The upward effect of the NPO on the German emission level is cancelled out by more abatement activity in the rest of Europe. Similarly, the downward effect of FITs on the German emission level if offset by less abatement activity in the rest of Europe. Adding FITs alongside the EU ETS thus does not offer any benefits from an atmospheric climate change perspective.

FITs do have a strong impact on the performance of the EU ETS. The EU ETS carbon price falls with 13% in 2030 (from €40 to €35, column 16, row 7). In 2020 and 2025 the impact of FITs on the EU ETS carbon price is -41% and -27% respectively (column 16, row 4-5). This result is in line with the earlier observation that FITs have the strongest impact on abatement activity in early years.

In the short and medium term (2015-2025) an NPO provides upward pressure to the carbon price, while the impact on the 2030 carbon price is near zero (-1%, column 22, row 7). This result is also in line with earlier results: in absence of an NPO the German power sector absorbs the retirement on nuclear generation capacity after 2025.

The combination of the NPO and FITs alongside the EU ETS leads to a 14% depreciation of the average carbon price in 2030, or €5 in absolute terms (column 25, row 7). The 10th percentile of the carbon price falls from €10 to €0 in 2020 and from €27 to €20 in 2025, compared to Scenario 2 (comparing column 6, row 4-5 and column 24, row 4-5). These

Figure 4.6: Mean Carbon price incl. EIs

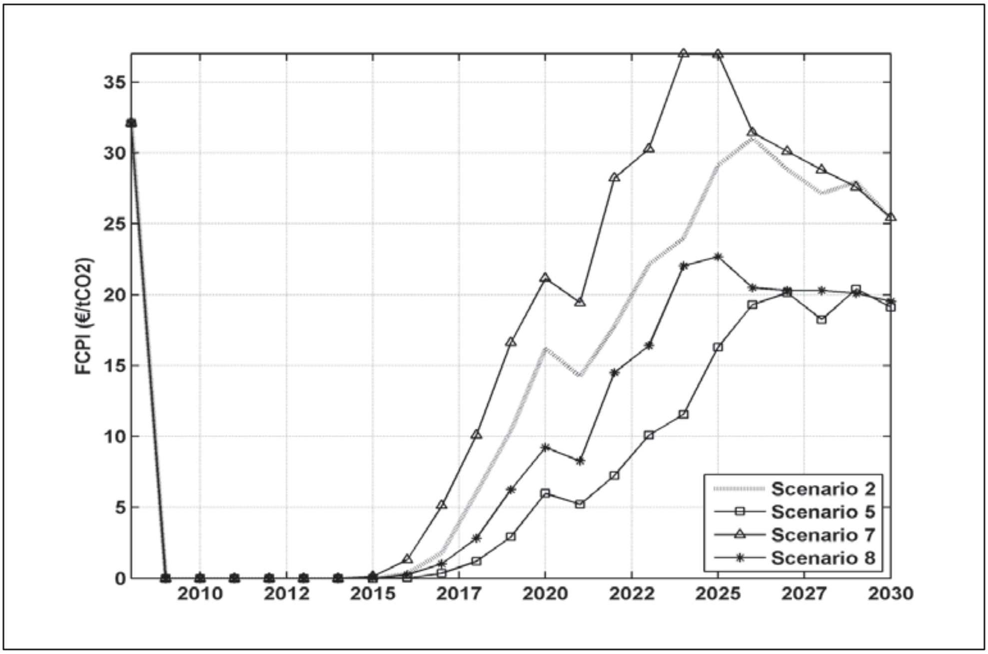


Figure 4.7: Mean Emission level incl. EIs

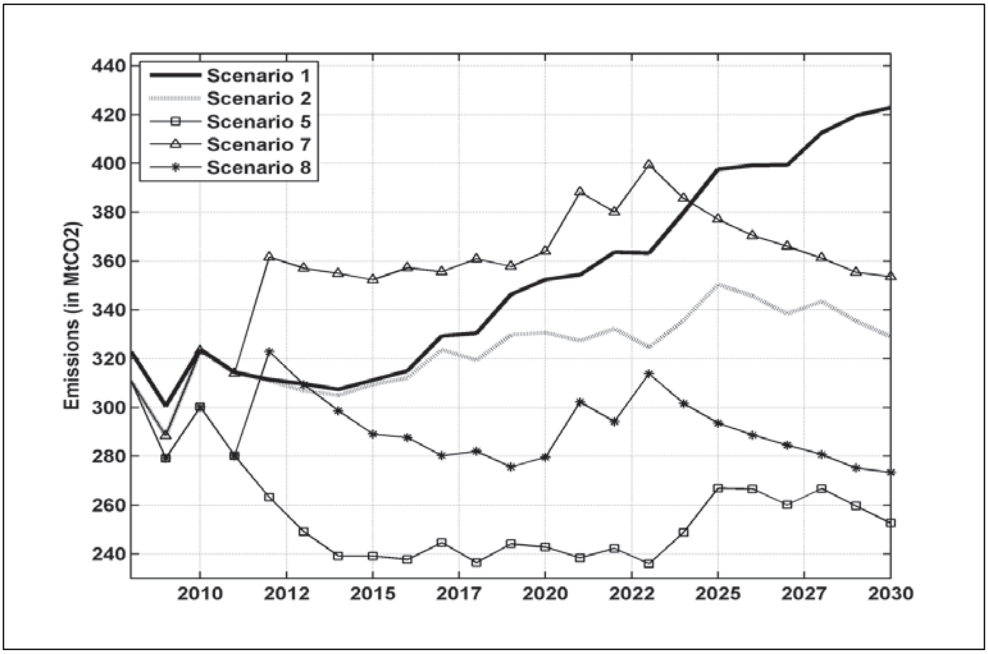


Table 4.4: Assuming 10 $MtCO_2$/yr abatement by EIs (10th perc/mean/90th perc)

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	**Output Parameter / Scenario**		**1** **No Instruments**			**2** **EU ETS**			**3** **FITs**			**4** **NPO**			**5** **EU ETS + FIT**			**6** **FIT + NPO**			**7** **EU ETS + NPO**			**8** **All Instruments**		
2			P10	**M**	P90	P10	**M**	P90	P10	**M**	P90	P10	**M**	P90	P10	**M**	P90	P10	**M**	P90	P10	**M**	P90	P10	**M**	P90
3	**Carbon price €/tCO_2**	2015				0	**0**	0							0	**0**	0				0	**0**	0	0	**0**	0
4		2020				0	**16**	40							0	**6**	23				0	**21**	40	0	**9**	24
5		2025				0	**29**	58							0	**16**	36				0	**37**	65	0	**23**	44
6		2030				1	**25**	50							0	**19**	34				0	**25**	50	0	**20**	35
7		2030 Diff.				€-15 -38%									€-21 -53%						€-15 -38%			€-20 -50%		
8	**Emissions in German power sector in $MtCO_2$**	2015				280	**310**	327							213	**239**	258				326	**353**	369	262	**289**	307
9		2020				297	**343**	374							214	**249**	274				322	**380**	415	249	**288**	313
10		2025				324	**376**	416							241	**283**	312				345	**407**	456	266	**314**	347
11		2030				305	**371**	427							229	**285**	326				329	**401**	457	254	**307**	347
12		2030 Diff.				+58 Mt +18%									-44 Mt -13%						+72 Mt +22%			-22 Mt -7%		
13	**All Emissions under EU ETS**	Mean in 2030				**1,519 Mt**									**1,514 Mt**						**1,517 Mt**			**1,511 Mt**		
14		Diff.				-29 Mt -2 %									-34 Mt -2 %						-31 Mt -2 %			-37 Mt -2 %		
15	**Abatement per year in Ger. power sector in $MtCO_2$**	**’08-‘30**				0	**+3**	+5							-4	**-1**	+1				+1	**+4**	+7	-3	**0**	+2
16		‘08-‘15				-4	**0**	+2							-14	**-10**	-8				+2	**+6**	+8	-7	**-3**	-1
17		‘16-‘20				-3	**+7**	+13							-5	**+2**	+7				-6	**+5**	+12	-8	**0**	+5
18		‘21-‘25				-4	**+7**	+15							-2	**+7**	+13				-7	**+5**	+15	-4	**+5**	+12
19		‘26-‘30				-14	**-1**	10							-11	**0**	+9				-16	**-1**	+10	-12	**-1**	+7

values indicate that, if economic growth rates remain low while fuel prices favour low-carbon alternatives, adding FITs and the NPO to the policy mix could seriously extend the period over which the EU ETS plays a marginal role in the policy mix.

4.4.4. Introducing External Instruments

We run all scenarios again, this time assuming that EIs trigger 10 $MtCO_2$ of abatement per year. The rationale for this number is based on the results in Table 4.3. Note that the introduction of FITs and the NPO alongside the EU ETS lowers the emission level in the German power sector by 56 $MtCO_2$ (column 25, row 12 in Table 4.3) In other words, abatement efforts are speeded up by 2.4 $MtCO_2$ per annum over the interval 2008-2030.[51] If we assume that the rest of Europe would be as effective to reduce the domestic emission level via the introduction of parallel instruments alongside the EU ETS, the impact of EIs would be approximately 13,6 $MtCO_2$ per annum.[52] In reality, parallel instruments seem to be primarily focused on the electricity sector, while roughly half of the coverage of the EU ETS is accounted for by other sectors. We represent this by assuming that the overall impact of EIs on all other sectors is not proportional in size to the impact of FITs and the NPO on the German electricity sector. Specifically, we assume that EIs have an annual impact of -10 $MtCO_2$ on the domestic emission level of EU member states.

Table 4.4 summarizes the results of our simulations. The new means for the carbon price and emission level are also depicted in Figures 4.6 and 4.7. Scenarios 1, 3, 4 and 6 are not affected by the introduction of EIs because the EU ETS is not part of the policy mix in these scenarios. Without an EU ETS in place, there is no direct link between abatement in other EU ETS sectors and the German power sector. Therefore, Scenarios 1, 3, 4 and 6 will not be discussed in this section, although we have reproduced the emission level of Scenario 1 in Figure 4.7 for ease of comparison to Figure 4.4. Scenario 2 in Table 4.3 remains our reference scenario for the results in this section. In that manner we can assess the combined impact of parallel instruments in the German power sector and elsewhere under the EU ETS on the performance of the EU ETS.

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[51] The interval 2008-2030 covers 23 years. 56/23=2.4 $MtCO_2$.

[52] The German power sector covers approximately 15% of all emissions under the EU ETS. Based on this number, the impact of external instruments would be: $\frac{2.4}{0.15} - 2.4 \approx 13.6\ \mathrm{MtCO_2}$.

EIs strongly affect the performance of the EU ETS as well as the German power sector. The 2030 carbon price in Scenario 2 falls with 38% from €40 to €25 (column 7, row 7 in Table 4.4), while the 2030 emission level in the German power sector increases with 18% to 371 $MtCO_2$ (column 7, row 12 in Table 4.4). Despite these effects, the overall emission level across Europe remains unchanged, irrespective of the policy mix that is under study.[53]

Turning to Scenario 8, we observe that EIs, FITs and the NPO collectively lead to an average depreciation of the EU ETS carbon price of 50% in 2030 (column 25, row 7). Note that the 10th percentile of the projected carbon price falls to €0 in 2020, 2025 and 2030 (column 24, row 4-6), indicating that redundancy of the EU ETS is possible if the economic growth rates remain low while fuel prices favour low-carbon alternatives.

In general, the observed effects of EIs on the EU ETS and the German power sector can be divided into 4 separate effects, each of which will be explained in detail below.

First, the EU ETS carbon price is generally lower across all scenarios. Secondly, the emission level in the German power sector is generally higher. Third, FITs lead to more abatement in Germany and have a stronger depreciating effect on the EU ETS carbon price after accounting for EIs. Fourth, a NPO leads to a stronger increase in the emission level in Germany and has a stronger appreciating effect on the EU ETS carbon price after accounting for EIs.

The upshot of a stronger depreciating effect of FITs and a stronger appreciating effect of the NPO is that their combined effect on the EU ETS remains largely unchanged. Specifically, the 2030 carbon price falls with €5 (comparing column 7, row 6 and column 25,

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[53] The negligible fall in the emission level of 2% that is observed across all scenarios in Table 4.4 can be attributed to the fact that that fuel switching in the rest of the EU is not accounted for. This modelling limitation is further discussed in Section 4.5.

row 6 in Table 4.4), equal to the results in the previous section (€-5, comparing column 7, row 6 and column 25, row 6 in Table 4.3). The four effects will now be discussed in more detail.

Lower carbon price – The carbon price depreciates following the introduction of EIs because abatement by EIs implies that less abatement needs to be triggered via the EU ETS to remain below the emission cap.

Higher emission level in the German power sector– Part of the abatement by EIs is offset via higher emissions in the German power sector. The emissions increase in the German power sector because the depreciated carbon price incentivizes operators of carbon intensive production capacity to produce more, at the expense of low-carbon production capacity. We illustrate this with the results of Scenario 2 in Tables 4.3 and 4.4 respectively. We observe a change in the 2030 emission level of +58 $MtCO_2$ (see column 7, row 12 in Table 4.4), equivalent to an average of +2.5 $MtCO_2$ per year over the interval 2008-2030. This implies that 25% of the abatement that is initiated by EIs (-10 $MtCO_2$/yr) is offset by higher emissions in the German power sector (+2.5 $MtCO_2$/yr).

The percentage of abatement by EIs that is offset in the German power sector is not constant across all scenarios because it depends on the composition of the electricity generation mix. Obviously, the policy mix influences the composition of the electricity generation mix. For example, in Scenario 5, only 14% of the abatement by EIs is offset in the German power sector (+32 $MtCO_2$ in 2030, comparing column 16, row 11 in Table 4.3 and 4.4). The percentage is significantly lower in Scenario 5 compared to Scenario 2 because FITs are included in the policy mix of Scenario 5. The larger the share of FIT-based operators in the electricity sector, the lower the responsiveness of the sector's emission level to changes in the carbon price. The emission level becomes less responsive because operators of FIT-based renewables enjoy the advantage of a fixed FIT and priority dispatch. Thereby, operators are protected against fluctuating market prices and are triggered to produce at full capacity.

Stronger depreciating effect of FITs on the carbon price – In the previous section, we determined that introducing FITs next to the EU ETS (going from Scenario 2 to 5) would lead to a carbon price depreciation of 13% in 2030. After accounting for the influence of foreign EIs, FITs lead to a carbon price depreciation of 24% in 2030 (difference between column 7, row 6 and column 16, row 6 in Table 4.4). Two key factors explain the increased depreciating effect of FITs on the carbon price.

First, FITs make the composition of the German electricity production mix, and thus the emission output, less responsive to market price fluctuations. Consequently, the German demand for EU ETS emission allowances also becomes less elastic. If the demand for emission allowances is less elastic, a stronger depreciation of the carbon price is required to offset the same amount of abatement via EIs.

Secondly, the weaker the EU ETS, the more abatement is triggered by FITs and the greater its carbon price depreciating effect. If the EU ETS is weaker because of EIs, more of the 'low hanging fruit' can be captured by FITs. The results in Tables 4.3 and 4.4 confirm this: adding FITs to the policy mix triggers an additional 86 $MtCO_2$ of abatement by 2030 if we take EIs into account (difference between column 7, row 11 and column 16, row 11 Table 4.4), while FITs only trigger 76 $MtCO_2$ of additional abatement if EIs are not taken into account (difference between column 7, row 11 and column 16, row 11 Table 4.3). In other words, the impact of FITs on investment behaviour increases by roughly 13% if the EU ETS is weakened by EIs. The fact that FITs trigger more abatement is reflected by a stronger depreciation of the carbon price.

Stronger appreciating effect of a NPO on the carbon price – In the previous section we determined that introducing a NPO next to the EU ETS (going from Scenario 2 to 7) would lead to a carbon price appreciation of 16% in 2020. After accounting for the influence of EIs, a NPO leads to a carbon price appreciation of 31% in 2020 (difference between column 7, row 4 and column 22, row 4 in Table 4.4). The reason for the stronger appreciating effect of a NPO on the carbon price is straightforward: because the equilibrium carbon price is lower after accounting for EIs, any nuclear generation capacity that is phased-out is now replaced by generation capacity with a higher carbon intensity than before. The higher emission intensity of electricity production provides greater support for the carbon price.

All of the four partial effects become more pronounced if we increase impact of EIs, while they become less pronounced if we decrease the impact of EIs.

4.4.5. Sensitivity Analysis

We will test the sensitivity of the results to changes in some of the parameter values. The parameters that are tested have in common that they may have a significant impact on the result, while empirical data is either unavailable or highly uncertain. The six parameters that are covered in the sensitivity analysis are provided in Table 4.5. The reference value and the assumed value for the sensitivity analysis are provided in columns 3 and 4 respectively. The symbol and equation of each parameter can be found in columns 5 and 6. Note that not all of the parameters have a symbol. This is either because the value of the parameter was direct input in the equation (this is true for sensitivity parameters 1 and 2), or because neither the parameter nor its value was explicitly accounted for in the equations because the reference value is 0% (this is true for sensitivity parameters 5 and 6).

For sensitivity parameters 1 to 4, the assumed value for the sensitivity analysis is 50% above the reference values that we have assumed so far. That large difference reflects the

Table 4.5: Parameters that are covered in the sensitivity analysis

#	Parameter	Reference value	Assumed value for sensitivity analysis	Symbol	Equation
1	Size of the two-year-ahead market	10%	15%	-	4.21
2	Size of the one-year-ahead market	40%	60%	-	4.23
3	Saturation limit	See col. 7 of Table 9.3	Reference value +50%	L^i	4.25
4	Discount rate	6%	9%	r	4.26
5	Anticipated %Δ of the carbon price	0% per annum	2.5% per annum	-	4.31
6	Technological experience curve effects	0%	See col.7 of Table 9.2	-	-

large uncertainty regarding the reference value. Because the difference is the same for each of these parameters, their relative impact on the results can be compared more easily. The reference value of parameters 5 and 6 is 0%. Therefore, the difference between the reference value and the value that is used in the sensitivity cannot be expressed as a percentage of the reference value.

Parameters five and six were not explicitly covered in the methodology section, therefore they require a more elaborate explanation, presented below. The results of the sensitivity analysis follow in Section 4.4.5.3.

4.4.5.1. ANTICIPATED PERCENTAGE CHANGE OF THE CARBON PRICE

So far, we have assumed that operators assume that the carbon price remains constant over the investment horizon when planning their investments (see Equation 4.31). Of course, if operators anticipate a different future price path of the carbon price, that may alter their investment decisions considerably. Therefore, we will re-run the previously tested scenario assuming that operators anticipate a 2.5% increase in the carbon price over the investment horizon. Equation 4.31 now becomes:

$$\mathrm{CF}^{\mathrm{i}}_{\mathrm{ts,t,ya}} = EPF^{i}_{ts,ya}\left[EC^{i}_{ts,t} * 1.025^{ya} + FC^{i}_{ts,t}(1+\mu^{i})^{ya*4} + OC^{i} * 1.01^{ya}\right] + FOC^{i} * 1.01^{ya}$$

$$for\ i = [1, \dots, 22],\ ts = [1, \dots, 16],\ t = [2008, \dots, 2030],\ ya = \{CT^{i} + 1, \dots, \mathrm{CT^{i}} + \mathrm{LT^{i}}\} \qquad (4.50)$$

The cost of emitting CO_2 per MW produced ($EC_{ts,t}^{i}$) is now multiplied by a factor 1.025^{ya}.

4.4.5.2. TECHNOLOGICAL EXPERIENCE CURVE EFFECTS

Technological experience curve effects refer to cost savings that are achieved when more experience is gained with a certain technology. Technological learning generally follows a law: each time the cumulative deployed capacity of a technology doubles, the costs fall by a constant percentage (Junginger *et al.*, 2010).[54] We cannot directly apply this law in the model because we would also have to account for the deployment of technologies in all other countries around the world. Instead, we opt for a simplified approach that relates deployment of a technology to cost savings. Specifically, we assume the following:

$$If\ \mathrm{INV}_{t-1}^{i} > 0 \begin{cases} \mathrm{CAPEX}_{t}^{i} = \mathrm{CAPEX}_{t-1}^{i}(1-\mathrm{TEC}^{i}) \\ OC_{t}^{i} = OC_{t-1}^{i}(1-TEC^{i}) \\ FOC_{t}^{i} = FOC_{t-1}^{i}(1-TEC^{i}) \end{cases} \quad \text{else} \begin{cases} \mathrm{CAPEX}_{t}^{i} = \mathrm{CAPEX}_{t-1}^{i} \\ OC_{t}^{i} = OC_{t-1}^{i} \\ FOC_{t}^{i} = FOC_{t-1}^{i} \end{cases}$$

$$for\ i = [1, \dots, 22],\ t = [2008, \dots 2030] \tag{4.51}$$

If investments in technology i are positive, the capital costs (CAPEX_{t}^{i}), other operating costs (OC_{t}^{i}), and fixed operating costs (FOC_{t}^{i}) fall with a fixed percentage TEC^{i}. The percentages that we have assumed are provided in column 7 of Table 9.3. Note that the percentages in Table 9.3 are technology specific: cost savings are 1% for technologies that we consider mature, 3% for technologies without any deployment so far and 2% for all other

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[54] Learning effects can also be driven by R&D activity, without any deployment of the technology (Klaassen *et al.*, 2005; Jamasb, 2006; Kobos *et al.*, 2006). In order not to complicate the analysis unnecessarily, we will not consider this type of learning here.

Figure 4.8: Mean Carbon Price

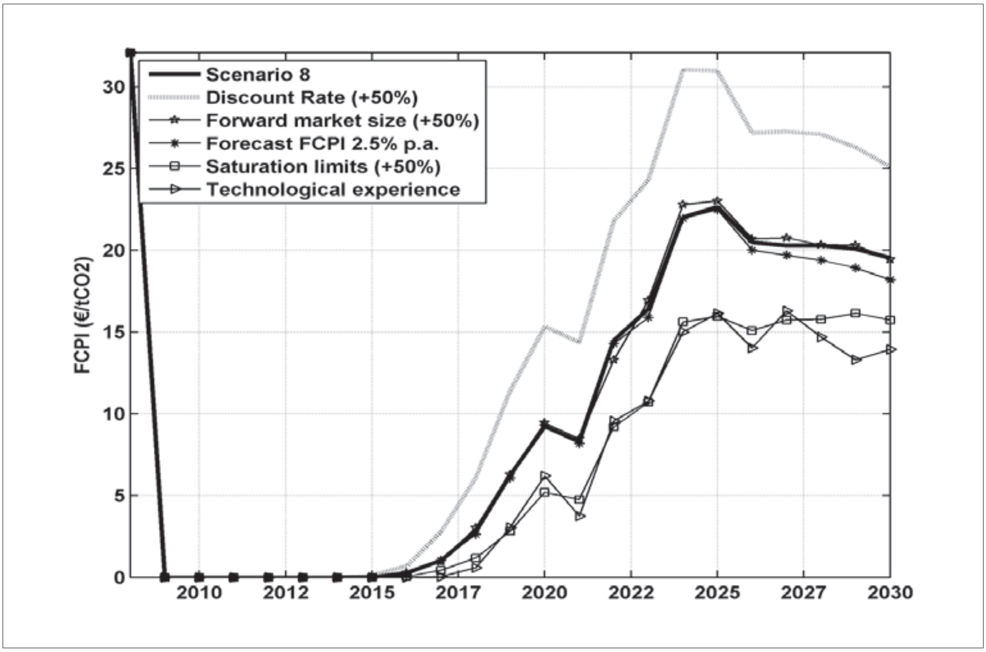
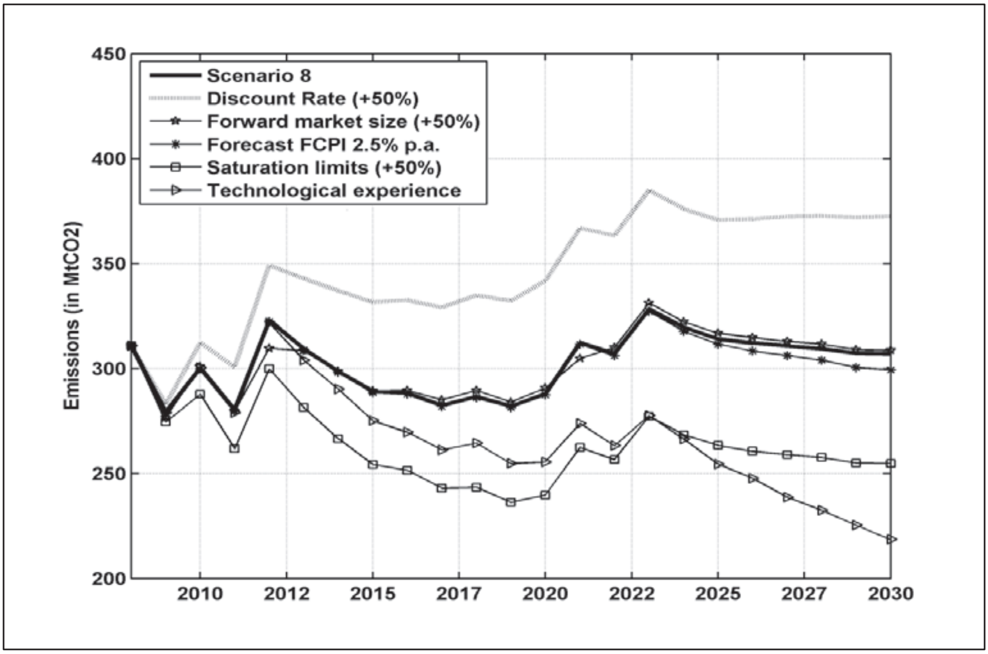


Figure 4.9: Mean Emission level



technologies. The differentiation reflects that a capacity doubling can be achieved much more easily for new technologies than for mature technologies.[55]

4.4.5.3. SENSITIVITY ANALYSIS RESULTS

We use Scenario 8 (with EIs) as the reference scenario and re-run that scenario with different assumptions. The results for the mean carbon price and emission level are shown in Figures 4.8 and 4.9 respectively. Note that parameters 1 and 2 in Table 4.5 are tested together in one scenario because they cover the same phenomenon (the size of the forward market).

Three factors have a relatively large effect on the results: the assumed discount rate, technological experience curve effects and the saturation limit. A fourth factor, the anticipation of operators regarding the future path of the carbon price, also has a moderate effect on the emission level and carbon price, although this effect is negligible compared to the former three effects.[56] The size of the forward market has a negligible effect on the simulation results. We will now discuss the role of the discount rate, technological experience curve effects and the saturation limit in more detail.

The key role of the discount rate is unsurprising as it has been widely discussed in academic literature (Hausman, 1979; Train, 1985; Jaffe *et al.*, 2003; Neuhoff, 2005). If the discount rate increases, the investor has a shorter time span to recoup the capital expense because the net present value of future cash flows become smaller. As a result, an investment

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[55] Over the total simulation window of 23 years, the assumed percentages imply that the costs of mature technologies may have fallen with a maximum of approximately 21% ($(1-0.01)^{23} \approx 0{,}79$) in 2030. Similarly, the costs of new technologies may have fallen with a maximum of 50%, while the costs of other technologies (with a learning percentage of 2%) may have fallen with a maximum of 37%. These maxima are only achieved if a technology is deployed in each of the 23 simulated years. If that criteria is not met, the cost saving will be less than the reported maximum. Note that we do not account for radical technological innovation that may be driven by a technological breakthrough.

[56] Note that the different outlook on the carbon price only affects investment behavior, but has not affected allowance banking strategies of German firms. Although a different outlook of German operators on the future carbon price may also change their allowance banking strategies, it is unclear how such strategy changes would precisely alter the shape of the supply curve of banked allowances in the ETSM (see Chapter 2, Equation 2.6). Therefore, we have not taken into account any changes to the allowance banking strategy in this simulation. A deeper understanding of the relationship between firm-level carbon price expectations, allowance stock sizes and banking strategies may therefore provide an interesting avenue for further research.

typically becomes less attractive, the higher the discount rate.[57] The corollary of the above is that FITs will also have a smaller impact on investment behaviour. This is reflected by a higher carbon price and a higher emission level (because the generation mix changes less rapidly if new investments become less attractive). Obviously, if the discount rate is lower than 6%, investments become more attractive.

Technological experience curve effects also have been widely discussed in academic literature (Wright, 1936; Rapping, 1965; Duke and Kammen, 1999; Grübler *et al.*, 1999; Junginger *et al.*, 2010) and have the opposite effect: they reinforce the impact of FITs on investment behaviour, the carbon price and the emission level. If FITs trigger the deployment of a certain technology, this leads to technological experience, which further improves the attractiveness of that technology. Consequently, we observe an even lower carbon price and emission level for Scenario 8 if we account for technological experience. Note that our method to account for technological experience curve effects and the assumed percentages (TEC^i) were simplistic and quite arbitrary respectively. However, considering that technological learning curve effects are a real phenomenon with a reinforcing effect on our results, the results in the previous sections could be considered conservative, provided that the reference discount rate and saturation limits are accurate. That is, FITs may well have an even stronger depreciating effect on the EU ETS carbon price if technological learning curve effects are triggered.

Finally, the saturation limit also has a considerable impact on the results, although its impact seems comparatively smaller than the role of the discount rate and technological learning. If the saturation limit increases, more will be invested in a particular technology at a given level of profitability. Obviously, instruments that improve the profitability of a

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[57] An exception to this general rule could be an investment with large positive cash flows in the short term, and negative cash flows in the longer term.

particular technology will therefore also have a greater impact on investment behaviour if the saturation limit increases.

4.5. Discussion

The above results reveal that the FITs and NPO that have been introduced by the German government in the German power sector have a considerable impact on the functioning of the EU ETS, while leaving the overall emission level in Europe unchanged. Despite the fact that the German power sector currently only encompasses around 15% of all emission under the EU ETS, the investment decisions that are made within the sector have strong implications for the performance of the EU ETS, and thereby for investment behaviour around Europe. The combined impact of FITs and the NPO in the German power sector alone are forecasted to lead to an average depreciation of the long-term EU ETS carbon price of around 14%, without reducing the overall emission level in Europe. FITs do trigger a substantial amount of abatement activity in the German power sector, while the NPO temporarily increases the emission level in the German power sector. However, if Germany speeds up abatement efforts in its domestic power sector via FITs, they also take the other sectors and countries under the EU ETS off the hook. The more (less) abatement is achieved in the German power sector, the less (more) abatement needs to be achieved elsewhere to remain below the EU ETS emissions cap.

If all parallel instruments that interact with the EU ETS are considered, the 2030 EU ETS carbon price is forecasted to fall by roughly 50%.

Given the large depreciating effect of parallel instruments on the EU ETS carbon price, the scheme is unlikely to deliver on its promise as the European flagship instrument. Complete redundancy of the EU ETS (with a permanent 0 euro carbon price) seems unlikely, although such a scenario cannot be ruled out if the economic growth rates remain low while fuel prices favour low-carbon alternatives. The EU ETS does not have to be the flagship instrument to ensure that the emission reduction targets are met. However, it is important to realize that, to a large extent, policymakers themselves seem to be responsible for the fact that the EU ETS is not playing its intended role in the policy mix.

The performance of the EU ETS is diminished quite strongly, despite the fact that Germany's policy mix conforms rather well to Mundell's Principle of Effective Market Classification. Mundell's principle states that instruments should be paired with the targets on which they have the most influence. Logically, the EU ETS has been paired with the target to reduce CO_2 emissions. FITs have been paired with the target to increase the deployment of renewable forms of electricity generation, and the NPO has been paired with the target to phase out nuclear generation capacity. The assignment of instruments to targets therefore does not seem to be the critical problem, at least regarding these two parallel instruments in Germany. Instead, the problem seems to be that the performance of the EU ETS is strongly linked to the pursuit of other political objectives. In that light, a reduction in the number of policy targets would seem necessary to ensure that the EU ETS is playing its intended role in the policy mix. Alternatively, the policy targets that interfere the strongest with the performance of the EU ETS could be set to a less ambitious level.

The stochastic approach that we have taken in this study reveals that uncertainty regarding the economic growth rate and the level of fuel prices is an important driver of the future emission level. Introducing instruments such as FITs, a NPO or an EU ETS to the policy mix may significantly lower the long-term emission level, yet economic growth and fuel price dynamics have the potential to partly (and in some cases fully) offset these instrument-induced effects on the emission level.

The decision to phase out nuclear generation capacity in the German power sector has a significant but temporary appreciating effect on the carbon price. Without a NPO in place, much of the nuclear generation capacity would have been retired towards 2030 anyway.

Two limitations of our methodology that may bias the estimation of the carbon price require mentioning. First, fuel switching is not accounted for outside the German power sector. In practice, parallel instruments depreciate the carbon price, which triggers other operators around Europe to emit more CO_2 by switching to a more CO_2 intensive fuel. In that manner, the abatement via parallel instruments is immediately offset. The immediate offset also provides immediate upward pressure on the carbon price. In our model, operators in other sectors can only offset abatement by parallel instruments in the long-term via investments. Short-term responsiveness, via fuel switching, is not accounted for. As a result, the sensitivity of the carbon price to parallel instruments may be slightly overstated. Although our results are unlikely to be strongly affected by this limitation, further research with a more detailed account of the power sectors in all 31 countries that participate in the EU ETS could take away this limitation. Secondly, speculation on the market for CO_2 allowances is not taken into account. Speculation can either amplify the volatility of the carbon price, or stabilize it. Its aggregate effect on the results is hard to predict, although long-term averages are once more unlikely to be strongly affected by this limitation.

4.6. Conclusion

In 2005, EU member-states chose for the European Union Emissions Trading Scheme (EU ETS) as a collective means to abate CO_2 emissions in energy intensive sectors. Any additional instrument that operates in parallel to the EU ETS, and also triggers abatement activity, directly (and often adversely) affects the performance of the EU ETS. Germany governs two key parallel instruments in the electricity sector: Feed-In Tariffs (FITs) and a Nuclear Phase Out (NPO). So far, however, is has been unclear to what extent the performance of the EU ETS is affected by these instruments. In this study, we perform a scenario analysis to quantitatively asses to what extent the performance of the EU ETS is affected by these parallel instruments.

The results indicate that the combined impact of FITs and the NPO in the German power sector is responsible for a 14% depreciation of the EU ETS carbon price. If all parallel instruments across Europe that interact with the EU ETS are considered, the 2030 EU ETS carbon price is forecasted to fall by roughly 50%. These results suggest that parallel instruments are a prominent driver behind the relatively low carbon prices that are witnessed in the market today. If policymakers want the EU ETS to play a leading role in the pursuit of long-term CO_2 reduction goals, they are advised to reconsider and simplify the existing policy mix before complicating it even further.

Although FITs and the NPO have serious implications for the performance of the EU ETS and investment behaviour around Europe, the overall CO_2 emission level in Europe remains unchanged. FITs do trigger a substantial amount of abatement activity in the German power sector, while the NPO temporarily increases the emission level in the German power sector. However, if Germany speeds up abatement efforts in its domestic power sector via FITs, they also take the other sectors and countries under the EU ETS off the hook. The more (less) abatement is achieved in the German power sector, the less (more) abatement is needed in other EU ETS sectors to remain below the EU ETS emissions cap.

5. CONCLUSION AND EPILOGUE

5.1. Revitalizing the EU ETS: in search of solutions

We started out this research project with the observation that, although the European Union has succeeded in placing a cap on CO_2 emissions from energy intensive sectors via the EU ETS, a second rather important objective has not yet been met. Specifically, the European Commission also pursues dynamic efficiency of the scheme (EC, 2013, 2014a). Dynamic efficiency implies that the EU ETS provides a credible incentive for investing in CO_2 abatement technologies in Europe. If the EU ETS is able to do that, it would likely prompt: more certainty to potential investors and with it willingness to act; and more technological learning effects and infrastructural development, each of which can bring down abatement costs significantly (Wright, 1936; Rapping, 1965; Duke and Kammen, 1999; Grübler *et al.*, 1999; Junginger *et al.*, 2010). This would allow the EU to attain its long-term emission reduction goals at a lower cost than would otherwise be the case.

This research project provides a deeper insight into the performance drivers of the EU ETS. The ultimate goal of the research is to assist policymakers to enhance the EU ETS effectiveness, and to achieve its dynamic efficiency goal.

In Section 5.2 of this epilogue we reflect on the results that have been obtained in the previous chapters. After that, we evaluate the results in Section 5.3 by establishing a link between the results in Chapter 2 and those in Chapter 4. Subsequently, in Section 5.4 we discuss the merit of proposals that have been put forward recently by European policymakers. Finally, in Section 5.5 we provide some interesting avenues for future research.

5.2. Key results and policy implications

First of all, in Chapter 2, we analysed to what extent the current design of the EU ETS translated itself into investment uncertainty for potential investors in CCS. Some literature suggests that CCS offers enough technical potential to account for 1/7th of the required global abatement efforts necessary to prevent the most devastating consequences of anthropogenic climate change (Pacala and Socolow, 2004). However, its development crucially hinges on the availability of a credible economic incentive for deployment. If such an incentive is created in a timely and structural manner, its deployment cost can decrease significantly. Thereby, CCS can not only contribute substantially to achieving long-term emission targets, but also do so at a substantially lower societal cost compared to scenarios without CCS as a technological option (*e.g.* Finnon, 2012; Riahi *et al.*, 2004). In that light, an EU ETS-based incentive that can structurally drive the deployment of CCS could be seen as a litmus test for the dynamic efficiency of the EU ETS. This is especially true given the high capital requirements and long lead times that are typically associated with CCS projects. Therefore, we explored in Chapter 2 to what extent potential investors are exposed to investment uncertainty under the current design of the EU ETS, and how amendments to the EU ETS design would alter their investment outlook.

In order to analyse the EU ETS impact more thoroughly, in the same chapter a dynamic stochastic simulation model of the EU ETS is developed to perform the required analysis. The EU ETS allowance price is an endogenous model variable that is dependent on the allowance supply regime, the demand for emission allowances, allowance banking strategies of firms and the abatement costs. Stochasticity is incorporated into the model to account for various types of uncertainty. The inclusion of the baseline emissions growth rate as a stochastic parameter (which is, in part, driven by the uncertain macro-economic growth rate) is particularly important in combination with the banking provision because it can lead to diverging pathways with regard to the CO_2 price and investment behaviour. In case of continued economic stagnation, allowance surpluses may build up, which can depreciate the allowance price for years or even decades into the future. In such a case, much less investment would be required to remain below the allowance cap, compared to a scenario with high economic growth rates. This may have serious ramifications for potential investors in CCS. In our view, the current literature on the topic generally does not sufficiently take these dynamics into account. We have performed a Monte Carlo simulation to generate probability distributions of output parameters.

The results of our study indicate that potential investors in CCS face considerable investment uncertainty under the EU ETS. Based on the abatement costs of various CCS types in the merit order of abatement technologies, the average scope for CCS across all types is forecasted to be 85 $MtCO_2$/yr by 2030 under the current design of the EU ETS. However, the standard deviation of this estimate is 70 $MtCO_2$/yr because the baseline emission level until 2030 is uncertain. The baseline emission level is driven by several factors with a key driver being the macro-economic growth rate. In the end, if economic growth rates are relatively high, substantial investments will be required over the next 15 year to remain below the ETS allowance cap. Alternatively, if the economy stagnates until 2030 the scope for CCS may be negligible or even non-existent. Given the long lead times towards completion of CCS abatement projects, the implied investment uncertainty is likely to be a significant obstacle towards deployment of CCS in reality, or, for that matter, any other technology with similar characteristics.

Furthermore, the analysis shows that a more restrictive allowance supply does not reduce the standard deviation of the expected scope for CCS, although the average scope does increase. Because the investment uncertainty remains, adjustments to the allowance supply do not seem to be an effective manner to structurally improve the strength of the EU ETS incentive mechanism for investments in CCS. In fact, even if a far-reaching restrictive policy would be adopted, a single downward economic shock could largely undo the positive impact of such a measure (see Section 2.3.3). Nevertheless, most EU ETS amendments that have recently been proposed involve restrictions on the supply of allowances (see also Section 5.4).

Therefore, if policymakers want to ensure that the EU ETS can structurally provide an incentive for technologies with high capital requirements and lead times such as CCS, they are advised to shift their efforts from supply restrictions to measures that can reduce the allowance price uncertainty that investors face. Such measures could, for example, take the form of price floors and ceilings. In any case, they should be geared towards a more stable investment incentives' outlook. Under the current design of the EU ETS, only waiting for the allowance price to (possibly only temporarily) reach the required level to trigger deployment does not seem to be a viable long-term strategy.

In Chapter 3 and 4, we turn to another issue that is known to influence the performance of the EU ETS: the interaction effects between the EU ETS and other instruments that operate in parallel to it. Parallel instruments often interact adversely with the performance of the EU ETS if such instruments, directly or indirectly, affect the CO_2 emission level in ETS sectors. Notable parallel instruments include incentives for the deployment of renewables and energy efficiency measures. If parallel instruments lead to a lower emission level in ETS sectors, they effectively operate as a substitute of the EU ETS. This is because abatement via parallel instruments implies that less abatement activity needs to be triggered via the EU ETS to remain below the allowance cap. As a result, such parallel instruments generally depreciate the EU ETS allowance price. Although this general mechanism has been identified before (see *e.g.* Hindsberger *et al.*, 2003; Morthorst, 2003), the exact scope and impact of these interactions on the EU ETS has so far remained unclear.

Therefore, both Chapter 3 and 4 of this research project have been dedicated to an in depth analysis of this issue.

In Chapter 3, we assessed under which conditions the EU ETS would become redundant as a result of the impact of parallel instruments. Here, we strictly define redundancy of the EU ETS as a scenario in which the allowance price permanently is €0. Also, we differentiated between two types of parallel instruments and investigated to what extent their effect on the performance of the EU ETS is different. The analysis can help policymakers to assess more precisely the extent to which parallel instruments undermine the performance of the EU ETS. In that manner, policymakers can weigh costs and benefits of introducing a parallel instrument more easily.

In this study, we built on the dynamic stochastic simulation model that was developed in Chapter 2 and introduced parallel instruments to it. Note that it is impossible to accurately model the drivers of all parallel instruments that are currently in place in Europe. Instead, we introduce them to the model in a rather stylized manner, namely by assuming their annual abatement impact (in $MtCO_2/yr$) on the emission levels in ETS sectors. By running a range of scenarios, each time with a higher impact on the emission level (with increments of 1 $MtCO_2/yr$), we assess at which impact level the EU ETS becomes redundant.

We differentiated between two classes of parallel instruments, termed Type 1 and Type 2 instruments. Type 1 instruments have been defined as instruments that aim at ETS sectors, and thereby reduce the carbon intensity of production of energy intensive sectors. A biomass co-firing mandate for the power sector is an example of a Type 1 instrument. In turn, Type 2 instruments have been defined as instruments that aim at non-ETS sectors and lower the demand for products that are produced by ETS sectors. Incentives for the deployment of decentralized renewables are a prominent example of a Type 2 instrument. Such instruments lower the demand for centrally produced electricity and thereby they lower the production volume and emission output of firms under the EU ETS.

Our analysis shows that Type 2 instruments have the greatest allowance price depreciating effect. This result can be explained by the fact that Type 2 instruments effectively take away the burden to abate CO_2 from ETS firms, while leaving all of the abatement options of ETS firms intact. Instead, if a Type 1 instruments leads to abatement of a tonne of CO_2, some of the technological abatement potential that is available in ETS sectors is used to do so. This implies that, in the case of Type 2 instruments, ETS firms retain more degrees of freedom to pursue future abatement efforts. This lowered burden on ETS firms is reflected by a more strongly depreciated CO_2 price.

Furthermore, the analysis shows that, if the collective impact of Type 1 and Type 2 instruments surpasses 40 $MtCO_2$/yr, the EU ETS is certain to become redundant. If the abatement impact surpasses 20 $MtCO_2$/yr, the future of the EU ETS is uncertain, and hinges on the macro-economic growth rate. The lower the economic growth rate, the greater the likelihood that the EU ETS becomes redundant. If the impact is below 20 $MtCO_2$/yr the EU ETS is unlikely to become redundant. However, these thresholds only hold under the assumption that policymakers and firms remain fully committed to the EU ETS. Otherwise the threshold levels are likely to be significantly below the reported values, indicating a considerably more vulnerable scheme. Firms may show a lack of commitment by dumping their emission allowances, while policymakers may trigger that response by expressing doubt regarding the future perspective of the EU ETS, by taking measures to that effect, or by implementing no measures at all when there is a deliberate call for intervention. In any case, even if firms and governments are fully committed to the EU ETS, the allowance price may be strongly depreciated if the impact is below the 20 $MtCO_2$/yr threshold but approaches that value.

If policymakers are interested in implementing a safeguard that would prevent the redundancy of the EU ETS via the impact of parallel instruments, they could consider the introduction of a cap on the use of parallel instruments. By setting the cap well below the 20 $MtCO_2$/yr threshold, redundancy or even marginally low allowance prices can be avoided. At the same time, the dynamic efficiency of the scheme would be stimulated. Although such a cap may be politically hard to establish in practice, it would provide a strong safeguard while also forcing national, local and regional governments in Europe to carefully select only those parallel instruments that offer the greatest local benefits and the least adverse impact on the EU ETS. In line with earlier results, a cap on parallel instruments should not only consider instruments that aim at ETS sectors, but explicitly also those that aim at non-ETS sectors and indirectly interfere with the performance of the EU ETS. In that manner, a more coherent and goal oriented policy mix can be organized.

In Chapter 4 we delve deeper into the topic of policy interaction. After having established in Chapter 3 that parallel instruments have the potential to strongly affect the performance of the EU ETS, we performed a case study to better understand to what extent the current performance of the EU ETS can be explained by this phenomenon. The fact that the EU ETS is currently performing worse than initially anticipated by many European policymakers is undisputable (EC, 2013, 2014a). The same holds for the adverse interaction effects between the EU ETS and parallel instruments. However, it remains unclear to what extent the former fact can be explained by the latter phenomenon.

The results of the case study indicate that the combination of Feed-In Tariffs (FITs) and the Nuclear Phase Out (NPO) in the German power sector depreciate the average EU ETS allowance price in 2030 by approximately €5 (or about 14% in relative terms). If all other parallel instruments that are in place across Europe are also taken into account in a stylized manner, we obtain a rough estimate of a €20 depreciation of the EU ETS allowance price (or about 50% in relative terms), compared to a scenario without any parallel instruments in place (see Section 4.4.2). We find that redundancy of the EU ETS is possible in the existing policy setting (including parallel instruments), albeit only in case of both continued sluggish economic growth rates and fuel prices that favour lower carbon alternatives.

In light of these results, policymakers that are interested in revitalizing the impact of the EU ETS on abatement activity are seriously advised to reconsider the composition of the policy mix in the energy and climate domain, to the extent that these policies directly or indirectly impact the EU ETS incentive strength. Simplification and recalibration of the policy mix may have a significant positive effect on the dynamic efficiency and overall strength of the EU ETS incentive. If policymakers want an EU ETS that structurally provides a strong incentive to energy-intensive sectors to reduce their CO_2 emissions, recalibration of the existing policy mix seems like a logical starting point.

We note that the two parallel instruments that were examined in the German power sector seem fairly well matched with the policy goals that they were intended to achieve. The NPO is a very effective means to accomplish a full phase out of nuclear energy, whereas FITs are also a rather direct means to stimulate the deployment of renewables. Given that the policy goals have been set, the choice for the respective instrument can be justified rather easily. To the extent that this is representative for all parallel instruments across Europe, policymakers are advised to first focus on reducing the number of parallel policy goals that have been set in the energy and climate domain. This advice applies to policymakers on all governmental levels, irrespective whether it is on the European, national, regional or local level. Alternatively, the parallel policy goals could be set to a different ambition level so as to avoid some of the adverse interactions. Subsequently, policymakers could focus on redesigning individual instruments in such a manner that adverse interactions are, at a minimum, reduced.

In short, the following lessons can be learned from the research that was presented in this thesis:

- The EU ETS provides investors with a high level of investment uncertainty making it unlikely that the scheme will trigger investments in CO_2 abatement technologies, which have a long lead-time and high capital requirements, like CCS (Chapter 2);
- Reducing the supply of emission allowances does not lower, and may even increase, the investment uncertainty that investors face (Chapter 2);
- If policymakers aim to improve the impact of the EU ETS on investment behaviour, they are advised to introduce measures that reduce CO_2 price uncertainty (Chapter 2).
- The EU ETS may become redundant if parallel instruments trigger more than 20 $MtCO_2$/yr abatement in EU ETS sectors. If some firms and/or policymakers have less than full commitment to the EU ETS that threshold is likely to be lower (Chapter 3);
- Capping the use of parallel instruments could both help to revitalize the EU ETS and would force policymakers to carefully select only those parallel instruments that offer the most favourable cost-benefit trade-off (Chapter 3)
- Parallel instruments that target non-ETS sectors have a stronger depreciating effect on the EU ETS CO_2 price than parallel instruments that are aimed at ETS sectors (Chapter 3);

- The FITs and NPO in the German power sector alone are responsible for a 14% depreciation of the EU ETS CO_2 price in 2030 (Chapter 4);
- All parallel instruments that are in operation today across Europe are estimated to depreciate the EU ETS allowance price by roughly 50% (Chapter 4);
- If policymakers aim to improve the impact of the EU ETS on investment behaviour, they are advised to reduce the number of policy targets (and the associated instruments) that interfere with the EU ETS (Chapter 4).

5.3. Epilogue: A final assessment of the scope for CCS under the EU ETS

In Chapter 2, we forecasted a scope for CCS in 2030 with a mean of 85 $MtCO_2$/yr and a standard deviation of 70 $MtCO_2$/yr. However, in that Base Case Scenario, we did not take parallel instruments into account. In Chapter 4, we concluded that parallel instruments have a significant depreciating effect on the EU ETS CO_2 price. A significantly lower CO_2 price is likely to lead to a significantly smaller deployment potential for CCS.

Table 5.1 summarizes the deployment levels of CCS in the German power sector under all of the tested scenarios in 2030. Note that, from a policy mix perspective, Scenario 2 from Chapter 4 (see Section 4.4.2) is the same as the Base Case simulation in Chapter 2. Both scenarios assume that the EU ETS is the only operational instrument.

If FITs, the NPO and External Instruments (EIs) are all added alongside the EU ETS,

Table 5.1: Cumulative CCS Deployment in 2030 in the German power sector

Scenario number	Scenario	Mean deployment in GW			
		No EIs		EIs = 10 $MtCO_2$	
1	No instruments	5.3	-17%	5.3	-17%
2	EU ETS (equiv. to Base Case in Chapter 2)	6.3	Ref.	5.7	-11%
5	EU ETS + FITs	5.4	-15%	5.1	-20%
7	EU ETS + NPO	5.6	-11%	4.3	-32%
8	EU ETS + FITs + NPO	3.8	-40%	3.1	-51%

the forecasted deployed capacity of CCS in the German power sector drops from 6.3 GW to 3.1 GW in 2030, equivalent to a fall of 51%. FITs and a NPO alone would result in a fall of the average investment potential of 40%. Note that introducing the NPO (going from Scenario 5 to 8) reduces the scope for CCS. This is because the removal of nuclear capacity from the production mix, starting in 2012, stimulates the deployment of other technologies to such an extent that the potential for CCS is reduced (compared to Scenario 5) by the time the technology is introduced to the market in 2025.

Although the average deployment levels are positive, we do note that investment uncertainty via the EU ETS remains a likely obstacle to deployment of CCS and other technologies. Also, various barriers to deployment have not been explicitly modelled (such as possible societal resistance, permitting procedures and local geological or infrastructural obstacles) which may further reduce the scope for CCS. In spite of that, we conclude that the potential for investments in CCS on the basis of the EU ETS allowance price incentive alone is further diminished significantly through the impact of parallel instruments across Europe.

5.4. Epilogue: current state of EU ETS policy development

Proposed amendment

In light of the fact that the EU ETS has, so far, not been able to meet prior expectations by many policymakers, various very recent proposals have been put forth in an effort to revitalize the EU ETS. In January 2014, the European Commission (EC, 2014a) proposed to add a Market Stability Reserve (MSR) to the EU ETS. The MSR was proposed because the European Commission noted that the current oversupply of emissions allowances, and the low CO_2 price, does not change existing investment patterns.

The MSR is a mechanism to adjust the number of emission allowances that are auctioned if the total number of banked allowances is outside a predefined range. Specifically, the number of allowances that is auctioned is temporarily reduced if the number of banked allowances is higher than 833 $MtCO_2$.[58] The allowances that are reduced from the auctionable allowances in a specific year are kept in the MSR. If the stock of banked allowances falls below 400 $MtCO_2$, 100 $MtCO_2$ of allowances are taken from the MSR and added to the auctionable volume in that year. The proposal states that the MSR should operate from the 1st of January 2021.

The MSR can be defended on the basis of two positive impacts. First, part of the currently observed low market price may be explained by the fact that some market participants have little confidence in the ability of the authorities to pass far-reaching proposals to revive the EU ETS, and take their positions in the market accordingly. Passing the MSR amendment would show that legislative action remains a viable option. Therefore, to the extent that the market price is suppressed by scepticism of market participants towards the legislative process itself, the MSR could make a difference. Secondly, the MSR would allow the authorities to withdraw allowances from being auctioned when the market price is relatively low, and allow them to reintroduce these allowances on the auction when the CO_2 price is higher. As a result, the authorities incur a higher auction revenue. Although this does not bring the EU any closer to its dynamic efficiency objective, policymakers are likely to see merit in higher auction revenues.

Interestingly, the potential to reap higher auction revenues may be a blessing in disguise. Member-state governments can determine how to use the auction revenues

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[58] The exact number of allowances that are reduced from the auctionable volume in year t is equal to 12% of the stock of banked allowances in year $t-1$, unless this number is less than 100 million allowances. Note that 100/0.12=833, which is equal to the upper bound of the predefined range.

themselves. However, the EU ETS directive (EC, 2009a) suggests in Article 10 that at least 50% of the revenues generated from the auctioning process should be used for one of the following options:

- To reduce greenhouse gas emissions (T1/T2);
- To develop renewable energy (T1/T2);
- To avoid deforestation and increase afforestation and reforestation;
- To apply CCS (T1);
- To encourage low-emission and public forms of transport (T2);
- To finance R&D in energy efficiency and clean technologies (T1/T2);
- To stimulate energy efficiency and insulation investments (T1/T2);
- To cover administrative expenses of the management of the EU ETS.

Many of the above investment options have great merit by themselves. However, in light of the discussion in the previous chapters, legislators should be careful when choosing their investment goal because many of the above options also adversely interact with the EU ETS. Between brackets, we have indicated in what manner the suggested options may interfere with the performance of the EU ETS. Here, T1 and T2 refer to Type 1 and Type 2 parallel instruments respectively, as defined in Chapter 3. Note that there are only two options that do not directly or indirectly interfere with the EU ETS performance. Higher auction revenues via the introduction of the MSR may therefore hurt the performance of the EU ETS if these revenues are spent on parallel instruments that adversely interact with the scheme.

In line with the suggestion in the EU ETS Directive, Germany has earmarked all of its auction revenues for a Special Energy and Climate Fund (in German: Sondervermögen Energie und Klimafonds, abbreviated EKF) (Esch, 2013). For 2014, the German government expects revenues into the fund totalling around 900 million euros. Around half of all of the revenues is spent on measures to stimulate renewable energy, energy efficiency, national climate action programmes, CO_2 building restoration and urban renewal with energy efficiency and climate neutrality as guiding principles. Poland, France, Romania, the Czech Republic and Hungary have made similar pledges to stimulate domestic climate-related projects, although none of them have earmarked 100% of the auction revenues (Esch, 2013).

All in all it is questionable whether the MSR, as foreseen, may really alter investment patterns in a meaningful way. In the end, the overall amount of emission allowances remains unchanged. Whether the allowances are immediately auctioned or whether they are temporary held in the MSR makes no fundamental difference as long as firms themselves hold more than enough allowances on stock to satisfy their immediate demand. The lower bound of the predefined range, 400 $MtCO_2$, ensures that this is the case.

Passed amendments

An amendment of EU ETS legislation that did pass (EC, 2014b) concerned a timetable to delay the auction of a total of 900 $MtCO_2$ of allowances. These allowances were reduced from the allowances that were set to be auctioned in 2014, 2015 and 2016, and are set to be redistributed in 2019 and 2020. Some market participants have suggested not to redistribute the allowances in 2019 and 2020, but to add these allowances to the MSR in the event that the amendment that introduces the MSR passes (EPRS, 2014). Similar to the MSR, the back loading proposal did not and will not have a large effect on the CO_2 price level, because the overall number of allowances does not change.

Another proposal that passed involves an adjustment of the annual reduction factor of the EU ETS allowance cap. In October of 2014, the European Council agreed to reduce GHG emissions by 40% in 2030 (compared to 1990). In order to achieve that target, the EU ETS allowance cap needs to be adjusted. Specifically, the emission allowance cap used to fall by 1.74% and will now fall by 2.2%, starting in 2021. This measure reduces the overall supply of emission allowances and, therefore, is an effective means to provide upward pressure for the CO_2 price.

All in all, the amendments that have passed may increase the average CO_2 price to some extent, while most proposals that are under serious consideration are unlikely to provide significant upward pressure to the CO_2 price. A more stringent adjustment, compared to the passed amendment, of the annual reduction factor was tested in Chapter 2. However, in that chapter, we concluded that an amendment with that magnitude is unlikely to transform the EU ETS into a credible incentive for investors that face large capital expenditures and long lead-times.

5.5. Avenues for future research

Interesting avenues for future research on emission trading schemes, and the EU ETS in particular are:

- Analyses of the relative cost-efficiency of various CO_2 abatement instruments (such as a CO_2 tax, emissions trading schemes, hybrid schemes, emission standards and others) that explicitly and realistically accounts for interactions between instruments in complex policy settings;
- Further development of analytical frameworks for policymakers to help prioritize and organize policy targets and instruments;

- Empirical analyses regarding emission allowance banking strategies. We have explicitly accounted for allowance banking strategies although our assumptions were not based on empirics. With greater knowledge on actual banking strategies and carbon price expectations of firms under the EU ETS, banking strategies can be modelled in a more detailed and ideally even dynamic manner;
- A more explicit account of the most important parallel instruments and EU ETS sectors across Europe. Our analysis in Chapter 4 captured the single largest sector under the EU ETS, and two of its most important parallel instruments. Yet, because the EU ETS spans 31 countries and a range of energy-intensive sectors a more explicit account of these other sectors (and associated instruments) would allow for an even more complete analysis.

6. BIBLIOGRAPHY

Abrell, J., Weigt, H., 2008. The interaction of emissions trading and renewable energy promotion. Economics of Global Warming. WP-EGW-05, Dresden University of Technology.

Acocella, N., Di Bartolomeo, G., Hughes Hallett, A., 2012. The theory of economic policy in a strategic context. Cambridge University Press, New York.

AGEB, 2013a. Brutostromerzeugung in Deutschland von 1990 bis 2013 nach Energieträgern. AG Energiebilanzen e.V.

AGEB, 2013b. Energieverbrauch in Deutschland im Jahr 2012. AG Energiebilanzen e.V.

Aksoy, H., Toprak, Z.F., Aytek, A., Ünal, N.E., 2004. Stochastic generation of hourly mean wind speed data. Renewable Energy 29, 2111-2131.

Allen, R.G.D., 1938. Mathematical Analysis for Economists. Macmillan and Co, London.

Amundsen, E.S., Mortensen, J.B., 2001. The Danish green certificate system: some simple analytical results. Energy Economics 23, 489-509.

Anandarajah, G., Strachan, N., 2010. Interactions and implications of renewable and climate change policy on UK energy scenarios. Energy Policy 38, 6724-6735.

Alberola, E., 2014. Climate and energy package in 2030: towards a new winning combination “40% +27% +20%” for the EU ETS? CDC Climat Research, Tendances Carbone 96, November 2014.

Alphen, K. van, van Voorst tot Voorst, Q., Hekkert, M.P., Smits, R.E.H.M., 2007. Societal acceptance of carbon capture and storage technologies. Energy Policy 35, 4368-4380.

Apraise, 2014. Understanding policy contexts and stakeholder behaviour for consistent and coherent environmental policies. APRAISE project, D5.3.

BDEW, 2013. BDEW-Strompreisanalyse Mai 2013 Haushalte und Industrie. Berlin.

Bennear, L.S., Stavins, R., 2007. Second-best theory and the use of multiple policy instruments. Environmental and Resource Economics 37, 111-129.

Black & Veatch, 2012. Cost and performance data for power generation technologies. USA.

Blyth, W., Bradley, R., Bunn, D., Clarke, C., Wilson, T., Yang, M., 2007. Investment risks under uncertain climate change policy. Energy Policy 35, 5766-5773.

Boemare, C., Quirion, P., 2002. Implementing greenhouse gas trading in Europe: lessons from economic literature and international experiences. Ecological Economics 43, 213-230.

Boemare, C., Quirion, P., Sorrell., S., 2003. The evolution of emissions trading in the EU: tensions between national trading schemes and the proposed EU directive. Climate Policy 3, S105-S124.

Böhringer, C., Koschel, H., Moslener, U., 2008. Efficiency losses from overlapping regulation of EU carbon emissions. Journal of Regulatory Economics 33, 299-317.

Böhringer, C., Löschel, A., Moslener, U., Rutherford, T.F., 2009. EU climate policy up to 2020: an economic impact assessment. Energy Economics 31, S295-S305.

Böhringer, C., Rosendahl, K.E., 2010. Green promotes the dirtiest: on the interaction between black and green quotas in energy markets. Journal of Regulatory Economics 37, 316-325.

Bömer, J., Brodersen, N., Hunke, D., Schüler V., Günther, H., Weisse, R., Fischer, J., Schäffer, M., Gaßner, H., 2010. Ocean energy in Germany. Ecofys, Project Number PPSMDE082434.

Boots, M., 2003. Green certificates and carbon trading in the Netherlands. Energy Policy 31, 43-50.

Broek, M. van den, Ramirez, A., Groenenberg, H., Neele, F., Viebahn, P., Turkenburg, W., Faaij, A., 2010. Feasibility of storing CO_2 in the Utsira formation as part of a long term Dutch CCS strategy: An evaluation based on a GIS/MARKAL toolbox. International Journal of Greenhouse Gas Control 4, 351-366.

Broek, M. van den, Veenendaal, P., Koutstaal, P., Turkenburg, W., Faaij, A., 2011. Impact of international climate policies on CO_2 capture and storage deployment: Illustrated in the Dutch energy system. Energy Policy 39, 2000-2019.

Bundesnetzagentur, 2010. EEG-Statistikbericht 2008 – Statistikbericht zur Jahresendabrechnung 2008 nach dem Erneubaren-Energien-Gesetz (EEG). Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen.

BUND, 2013. Geplante und im Bau befindliche Kohlekraftwerke. Bund für Umwelt und Naturschutz Deutschland.

Bundestag, 2004. Erneuerbare-Energien-Gesetz vom 21. Juli 2004 (BGBl. I S. 1918), zuletzt geändert durch Artikel 1 des Gesetzes vom 7. November 2006 (BGBl. I S. 2550).

Bundestag, 2009. Erneuerbare-Energien-Gesetz vom 25. Oktober 2008 (BGBl. I S. 2074), zuletzt geändert durch Artikel 1 des Gesetzes vom 28. Juli 2011 (BGBl. I S. 1634).

Bundestag, 2010. Entwurf eines Elften Gesetzes zur Anderung des Atomgesetzes. 17/3051.

Bundestag, 2012. EEG — Gesetz für den Vorrang Erneuerbarer Energien Konsolidierte Fassung des Gesetzestextes in der ab 1. Januar 2012 geltenden Fassung.

BUNR, 2013. Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland. Bundesministerium für Umwelt Naturschutz und Reaktorsicherheit, Juli 2013.

BWT, 2013. Zahlen und Fakten Energiedaten, 20-08-2013, Bunderministerium für Wirtschaft und Technologie.

Bye, T., Bruvoll, A., 2008. Multiple instruments to change energy behaviour: The emperor's new clothes? Energy Efficiency 1, 373-386.

Cass, L., 2005. Norm entrapment and preference change: the evolution of the European Union position on International Emissions Trading. Global Environmental Politics 5, 38-60.

Chevallier, J., 2009. Carbon futures and macroeconomic risk factors: A view from the EU ETS. Energy Economics 31, 614-625.

Conrad, K., Kohn, R.E., 1996. The US market for SO_2 permits: policy implications of the low price and trading volume. Energy Policy 24, 1051-1059.

Convery, F.J., 2009. Origins and developments of the EU ETS. Environmental Resource Economics 43, 391-412.

Crousillat, E.O., 1989. Incorporating risk and uncertainty in power system planning. Energy series paper no. 17, The World Bank.

Damro, C., Luaces Méndez, P., 2003. Emissions trading at Kyoto: from EU resistance to union innovation. Environmental Politics 12, 71-94.

Damro, C., Hardie, I., MacKenzie, D., 2008. The EU and climate change policy: law, politics and prominence at different levels. Journal of Contemporary European Research 4, 179-192.

DEA, 2012. Technology data for energy plants. Copenhagen.

De Jonghe, C., Delarue, E., Belmans, R., D'haeseleer, W., 2009. Interactions between measures for the support of electricity from renewable energy sources and CO_2 mitigation. Energy Policy 37, 4743-4752.

Delbeke,J., 2006. EU environmental law:the EU greenhouse gas emissions trading scheme. EU Energy Law Volume IV, Claeys & Casteels, Leuven, Belgium.

Del Rio, P., 2007. The interaction between emissions trading and renewable electricity support schemes. An overview of the literature. Mitigation and Adaptation Strategies for Global Change 12, 1363-1390.

Del Rio, P., 2009. Interactions between climate and energy policies: the case of Spain. Climate Policy 9, 119-138.

Di Bartolomeo, G., Hughes Hallett, A., and Acocella, N., 2011. Tinbergen controllability and n-player LQ-games. Economics Letters 113, 32-34.

Duke, R., Kammen, D., 1999. The economics of energy market transformation initiatives. The Energy Journal 20, 15-64.

EC, 1991. A Community strategy to limit carbon dioxide emissions and to improve energy efficiency. Communication from the Commission to the Council. SEC (91) 1744 final, 14 October 1991.

EC, 1996. Communication from the Commission under the UN framework convention on climate change. COM (96) 217 final.

EC, 1998. Climate Change: Towards a Post-Kyoto Strategy. Commission communication to the Council and Parliament. COM (98) 353.

EC, 1999. Preparing for implementation of the Kyoto Protocol. Commission communication to the Council and the Parliament. COM (99) 230 final.

EC, 2000. Greenpaper on Greenhouse Gas Emission Trading within the EU. Commission communication to the Council and Parliament. COM (00) 87.

EC, 2003. Directive 2003/87/EC of the European Parliament and of the Council establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC.

EC, 2004. Directive 2004/101/EC of the European Parliament and of the Council amending Directive 2003/87/EC establishing a scheme for greenhouse gas emission allowance trading within the Community, in respect of the Kyoto Protocol's project mechanisms.

EC, 2009a. Directive 2009/29/EC of the European parliament and of the council of 23 April 2009 amending directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the community. Official Journal of the European Union, L 140/63.

EC, 2009b. Directive 2009/31/EC of the European Parliament and of the council of 23 April 2009 on the geological storage of carbon dioxide. Official Journal of the European Union, L 140/114.

EC, 2010. Emissions Trading: EU ETS emissions fall more than 11% in 2009. European Commission, IP/10/576.

EC, 2011. Emissions Trading: EU ETS emissions increased in 2010 but remained well below pre-crisis level. European Commission, IP/11/581.

EC, 2013. Green paper – A 2030 framework for climate and energy policies. COM/2013/0169. European Commission.

EC, 2014a. Proposal for a decision of the European Parliament and of the council concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and amending Directive 2003/87/EC. COM/2014/20/2.

EC, 2014b. Commission regulation (EU) No 176/2014 of 25 February 2014 amending Regulation (EU) No 1031/2010 in particular to determine the volumes of greenhouse gas emission allowances to be auctioned in 2013-20. Official Journal of the European Union, L 56/11.

EDF, 2012. Flamanville EPR : costs revised, still on schedule. Press release 2012/12/03, Paris.

EEA, 2011a. Resource efficiency in Europe policies and approaches in 31 EEA member and cooperating countries. European Environmental Agency Report, No 5/2011.

EEA, 2011b. Annual European Union greenhouse gas inventory 1990-2009 and inventory report 2011. European Environment Agency, Technical Report No.2.

EEA, 2012. Greenhouse gas data viewer. European Environment Agency, August 2013.

Ellerman, A.D., Joskow, P.L., Schmalensee, R., Montero, J.P., Bailey, E.M., 2000. Markets for clean air. Cambridge University Press.

Enkvist, P., Naucler, T., 2009. Pathways to a low-carbon economy. McKinsey Climate Change Special Initiative.

Enkvist, P., Dinkel, J., Lin, C., 2010. Impact of the financial crisis on carbon economics: version 2.1 of the global greenhouse gas abatement cost curve. McKinsey Climate Change Special Initiative.

ENTSOE (2014) Consumption data – Hourly load values of a specific country. https://www.entsoe.eu/data/data-portal/consumption/Pages/default.aspx.

EPRI, 1999. A framework for hedging the risk of greenhouse gas regulations. Palo Alto, CA. TR-113642.

EPRS, 2014. Reform of the EU carbon market – from backloading to the market stability reserve. Briefing October 2014. European Parliamentary Research Service.

Esch, 2013. Using EU ETS auctioning revenues for climate action. Germanwatch e.V., Berlin.

EP, 2010. Overview of energy efficiency measures of European Industry. Directorate-General for Internal Policies, IP/A/ITRE/NT/2010-08.

Finnon, D., 2012. Efficiency of policy instruments for CCS deployment. Climate Policy 12, 237-254.

Frankhauser, S., Hepburn, C., Park, J., 2010. Combining multiple climate policy instruments: how not to do it. Climate Change Economics 1, 1-17.

Freeman, A.M., Burtraw, D., Harrington, W., Krupnick, A.J., 1992. Weighing environmental externalities: how to do it right. The Electricity Journal 5, 18-25.

GE Electric, 2010. Western wind and solar integration study. NREL/SR-550-47434.

Gerbert, P., Herhold, P., Heuskel, D., Klose, F., 2013. Trendstudie 2030+ Kompetenzinitiative Energie des BDI. Boston Consulting Group.

Glachant, M., 2001. Implementing European environmental policy: the impacts of directives in the member states. Edward Elgar Publishing.

Graus, W., Sreenivasamurthy, U., Wesselink, B., 2009. EU climate policy impact in 2020. Ecofys, June 2009.

Grubb, M., Vrolijk, C., Brack, D., 1999. The Kyoto Protocol: A Guide and Assessment. Earthscan London.

Grubb, M., Köhler, J., Anderson, D., 2002. Induced technical change in energy and environmental modeling: analytical approaches and policy implications. annual review of energy and the environment 27, 271-308.

Grubb, M., Neuhoff, K., 2006. Allocation and competitiveness in the EU emissions trading scheme: policy overview. Climate Policy 6, 7-30.

Grübler, A., Nakićenović, N., Victor, D.G., 1999. Dynamics of energy technologies and global change. Energy Policy 27, 247-280.

Harrison, D., Sorrell, S., Radov, D., Klevnas, P., Foss, A., 2005. Interactions of the EU ETS with green and white certificate schemes. National Economic Research Associates.

Hart, E.K., Jacobson, M.Z., 2011. A Monte Carlo approach to generator portfolio planning and carbon emissions assessments of systems with large penetrations of variable renewables. Renewable Energy 36, 2278-2286.

Hart, E.K., Stoutenberg, E.D., Jacobson, M.Z., 2012. The potential of intermittent renewables to meet electric power demand: current methods and emerging analytical techniques. Proceedings of the IEEE 100, 322-334.

Haszeldine, R.S., 2009. Carbon capture and storage: how green can black be? Science 325, 1647-1652.

Hausman, J.A., 1979. Individual discount rates and the purchase and utilization of energy-using durables. Bell Journal of Economics 10, 33-54.

Henkel, J., Lenck, T., 2013. Prognose der Stromabgabe an Letztverbraucher bis 2018. Energy Brainpool, Berlin.

Hetzer, J., Yu, D.C., Bhattarai, K., 2008. An economic dispatch model incorporating wind power. IEEE Transactions on Energy Conversion 23, 603-611.

Hindsberger, M., Nybroe, M.H., Ravn, H.F., Schmidt, R., 2003. Co-existence of electricity, TEP, and TGC markets in the Baltic Sea region. Energy Policy 31, 85-96.

Hobbs, B.F., Rijkers, F.A.M., Boots, M.G., 2005. The more cooperation, the more competition? A Cournot analysis of the benefits of electric market coupling. The Energy Journal 26, 69-97.

Hollands, K.G.T., Huget, R.G., 1983. A probability density function for the clearness index, with applications. Solar Energy 30, 195-209.

Huijts, N.M.A., Midden, C.J.H., Meijnders, A.L., 2007. Societal acceptance of carbon dioxide storage. Energy Policy 35, 2780-2789.

ICAP, 2014. Emissions trading worldwide status report 2014. International Carbon Action Partnership.

IEA, 2009. World energy outlook 2009. OECD/IEA, Paris.

IEA, 2010. Energy technology perspectives – Scenarios and strategies to 2050. International Energy Agency.

IEA/NEA, 2010. Projected costs of generating electricity. Paris.

IEA, 2011.Technology roadmap – carbon capture and storage in industrial applications. OECD/IEA and UNIDO.

IEA, 2013. Tracking clean energy progress 2013. IEA Input to the Clean Energy Ministerial. Paris.

IEA-RETD, 2013. Cost and business comparisons of renewable vs. non-renewable technologies. Madrid.

IER, 2010. Die Entwicklung der Energiemärkte bis 2030, Energieprognose 2009. Untersuchung Im Auftrag des Bundesministeriums für Wirtschaft und Technologie, Berlin.

IMF, 2014. IMF cross country macroeconomic statistics. Open data for Africa.

IndexMundi, 2014. Uranium monthly price. http://www.indexmundi.com/commodities/?commodity=uranium&months=360.

Interact, 2003. Interaction in EU climate policy. Science Policy Research Unit, University of Sussex.

IPCC, 1990. Climate change: the IPCC scientific assessment. Houghton, J.T., *et al*. (eds.). Cambridge University Press.

IPCC, 2005. Special report on carbon dioxide capture and storage. Metz, B., *et al*. (eds.). Cambridge University Press.

IPCC, 2007. Fourth assessment report: climate change 2007. Pachauri, R.K., *et al*. (eds.)., IPCC, Geneva, Switzerland.

IPCC, 2013. Fifth assessment report: climate change 2013. Pachauri, R.K., *et al*. (eds.). Cambridge University Press.

IRENA, 2012. Renewable energy technologies: cost analysis series: wind power. Abu Dhabi.

IRENA, 2013. Renewable power generation costs in 2012: An Overvi ew. Abu Dhabi.

Jaffe, A.B., Newell, R.G., Stavins, R.N., 2003. Technological change and the environment. In: Mäler, K.G., Vincent, J. (Eds.), Handbook of environmental economics, North-Holland, Amsterdam, 461-516.

Jaffe, A.B., Newell, R.G., Stavins, R.N., 2005. A tale of two market failures: technology and environmental policy. Ecological Economics, 164-174.

Jamasb, T., 2006. Technical change theory and learning curves: patterns of progress in electricity generation technologies. Energy Journal 28, 51-71.

Jensen, S.G., Skytte, K., 2003. Simulataneous attainment of energy goals by means of green certificates and emission permits. Energy Policy 31, 63-71.

JRC, 2012. 2012 PV status report. Luxembourg.

JRC, 2013. 2012 JRC wind status report. Technology, market and economic aspects of wind energy in Europe. Luxembourg.

Junginger, M., van Sark, W., Faaij, A., 2010. Technological learning in the energy sector. Edward Elgar Publishing.

Kautto, N., Arasto, A., Sijm, J., Reck, P., 2012. Interaction of the EU ETS and national climate policy instruments – impact on biomass use. Biomass and Bioenergy 38, 117-127.

Klaassen, G., Asami, M., Larsen, K., Sundqvist, T., 2005. The impact of R&D on innovation for wind energy in Denmark, Germany and the United Kingdom. Ecological Economics 54, 227-240.

KNMI, 2014. Potentiële wind in Nederland. Klimaatdata en advies. Koninklijk Nederlands Meteorologisch Instituut.

Kobos, P.H., Erickson, J.D., Drennen, T.E., 2006. Technological learning and renewable energy costs: implications for US renewable energy policy. Energy Policy 34, 1645-1658.

Krey, V., Martinsen, D., Wagner, H.J., 2007. Effects of stochastic energy prices on long-term energy-economic scenarios. Energy 32, 2340-2349.

Kumar, R., Umanand, L., 2005. Estimation of global radiation using clearness index model for sizing photovoltaic system. Renewable Energy 30, 2221-2233.

Laurikka, H., Koljonen, T., 2006. Emissions trading and investment decisions in the power sector – a case study in Finland. Energy Policy 34, 1063-1074.

Lewis, M., 2008. Carbon emissions: getting tighter: why the Phase-2 cap is even tougher than it looks. Global Markets Research Deutsche Bank.

Linares, P., Santos, F.J., Ventosa, M., 2008. Coordination of carbon reduction and renewable energy support policies. Climate policy 8, 377-394.

Lun, I.Y.F., Lam, J.C., 2000. A study of Weibull parameters using long-term wind observations. Renewable Energy 20, 145-153.

Lundberg, H., Corless, V., Havlikova, D., Laird, B., Rygnestad, L., 2012. Renewable energy policies in Europe a mapping of existing and planned support schemes for renewable energy development in 31 European countries. The Bellona Foundation.

Majone, G., 1989. Evidence, argument and persuasion in the policy process. New Haven and London, Yale University Press.

Matthes, F.C., Harthan, R.O., Loreck, C., 2011. Atomstrom aus Frankreich? Kurzfristige abschaltungen deutscher Kernkraftwerke und die Entwicklung des Strom-Austauschs met dem Ausland. Kurzanalyse für die Unweltstiftung WWF Deutschland, Ökoinstitut, Berlin.

Mavrakis, D., Konidari, P., 2002. Classification of the design characteristics of emission trading schemes. European Environment 13, 48-66.

Mckibbin, W.J., Wilcoxen, P.J., 2002. The role of economics in the climate change policy. Journal of Economic Perspectives 16, 107-129.

Mirkhani, S., Saboohi, Y., 2012. Stochastic modeling of the energy supply system with uncertain fuel price – A case of emerging technologies for distributed power generation. Applied Energy 93, 668-674.

Metz, B., de Coninck, H.C., 2007. CO_2 capture and storage: a future for coal? ECN Policy Studies. ECN-B-07-020.

Moreira, A., Rocha, K., David, P., 2004. Thermopower generation investment in Brazil – economic conditions. Energy Policy 32, 91-100.

Morris, J.F., Reilly, J.M., Paltsev, S., 2010. Combining a renewable portfolio standard with a cap-and-trade policy: a general equilibrium analysis. MIT Joint Program on Science and Policy of Global Change, report no. 187.

Morthorst, P.E., 2001. Interactions of a tradable green certificate market with a tradable permits market. Energy Policy 29, 345-353.

Morthorst, P.E., 2003. National environmental targets and international emission reduction instruments. Energy Policy 31, 73-83.

Mundell, R., 1962. The appropriate use of monetary and fiscal policy for internal and external stability. IMF Staff Papers, 70-79.

Neuhoff, K., 2005. Large-scale deployment of renewables for electricity generation. Oxford review of economic policy 21, 88-110.

Neuhoff, K., Schopp, A., Boyd R., Stelmakh, K., Vasa, A., 2012. Banking of Surplus Emission Allowances. Discussion Papers. Deutsches Institüt für Wirtschaftsforschung.

NREL, 2012. Renewable electricity futures study. NREL/TP-6A20-52409, Golden, CO.

Odenberger, M., Kjärstad, J., Johnsson, F., 2008. Ramp-up of CO_2 capture and storage within Europe. International Journal of Greenhouse Gas Control 2, 417- 438.

Odenberger, M., Johnsson, F., 2010. Pathways for the European electricity supply system to 2050—The role of CCS to meet stringent CO_2 reduction targets. International Journal of Greenhouse Gas Control 4, 327 - 340.

Oikonomou, V., 2010. Interactions of white certificates for energy efficiency and other energy and climate policy instruments. Doctoral dissertation. University of Groningen, the Netherlands.

Oikonomou, V., Jepma, C.J., 2008. A framework on interactions of climate and energy policy instruments. Mitigation and Adaptation Strategies for Global Change 13, 131-156.

Olsina, F., Garcés, F., Haubrich, H.J., 2006. Modeling long-term dynamics of electricity markets. Energy Policy 34, 1411-1433.

Pacala, S., Socolow, R., 2004. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. Science 29, 1413-1422.

Papineau, M., 2006. An economic perspective on experience curve and dynamic economies in renewable energy technologies. Energy Policy 34, 422-432.

PBL, 2014. Trends in global CO2 emissions. PBL Netherlands Environmental Assessment Agency and European Commission Joint Research Centre.

Pearson, M., Smith, S., 1991. The European carbon tax: an assessment of the European Commission's proposals. The Institute for Fiscal Studies, London.

Pizer, W., 1999. Choosing price or quantity controls for greenhouse gases. Climate Change Issues Brief 17, Resources for the future, Washington DC.

Pizer, W.A., 2002. Combining price and quantity controls to mitigate global climate change. Journal of Public Economics 85, 409-434.

PVGIS, 2012. Geographical assessment of solar resource and performance of photovoltaic technology. Joint Research Centre, European Commission.

Rapping, L., 1965. Learning and world war II production functions. The Review of Economic Statistics 47, 81-86.

Rathmann, M., 2007. Do support systems for RES-E reduce EU-ETS-driven electricity prices? Energy Policy 35, 342-349.

Reuters, 2014. China's national carbon market to start in 2016 –official. Retrieved on 09-05-2015. http://uk.reuters.com/article/2014/08/31/ china-carbontrading-idUKL3N0R107420140831.

Riahi, K., Rubin, E.S., Schrattenholzer, L., 2004. Prospects for carbon capture and sequestration assuming technological learning. Energy 29, 1309-1318.

Rothwell, G., 2006. A real options approach to evaluating new nuclear power plants. Energy Journal 27, 37-53.

Sbragia, A.M., 1998. Institution-building from below and above: the European Community in Global Environmental Politics. In Sandholts, W., Stone Sweet, A. (eds.), European Integration and Supranational Governance. Oxford University Press, 283-303.

Schmidt, T.S., Born, R., Schneider, M., 2012. Assessing the costs of photovoltaic and wind power in six developing countries. Nature Climate Change 2, 548-553.

Schreurs, M.A., Tiberghien, Y., 2007. Multi-level reinforcement: explaining European Union leadership in climate change mitigation. Global Environmental Politics 7, 19-46.

Schultz, R., Agemar, T., Alten, A.J., Kühne, K., Maul, A.A., Pester, S., Wirth, W., 2007. Aufbau eines geothermischen Informationssystems für Detuschland. Erdöl Erdgas Kohle 123, 76-81.

Seguro, J.V., Lambert, T.W., 2000. Modern estimation of the parameters of the Weibull wind speed distribution for wind energy analysis. Journal of Wind Engineering and Industrial Aerodynamics 85, 75-84.

Siikamäki, J.,Munnings, C., Ferris, J., 2012. The European Union Emissions Trading System. Resources for the Future, Washington, November 2012.

Sijm, J., Neuhoff, K., Chen, Y., 2006. CO_2 cost pass-through and windfall profits in the power sector. Climate Policy 6, 49-72.

Silverberg, G., Verspagen, B., 2003. Breaking the waves: a Poisson regression approach to Schumpeterian clustering of basic innovations. Cambridge Journal of Economics 27, 671-693.

Sinn, H.W., 2011. The green paradox: a supply-side approach to global warming. MIT Press.

Smith, A., Sorell, S., 2001. Interaction between environmental policy instruments: carbon emissions trading and integrated pollution prevention and control. International Journal of Environment and Pollution 15, 22-41.

Sorrell, S., Harrison, D., Radov, D., Klevnas, P., Foss, A., 2009. White certificate schemes: economic analysis and interactions with the EU ETS. Energy Policy 37, 29-42.

Sorrell, S., Sijm, J., 2003. Carbon trading in the policy mix. Oxford Review of Economic Policy 19, 420-437.

Söderholm, P., 2000. Fuel flexibility in the West European power sector. Resources Policy 26, 157-170.

Söderholm, P., 2001. Fossil fuel flexibility in West European power generation and the impact of system load factors. Energy Economics 23, 77-97.

Stangeland, A., 2007. A model for the CO_2 capture potential. International Journal of Greenhouse Gas Control 1, 418-429.

Stefánsson, V., 2002. Investment cost for geothermal power plants. Geothermics 31, 263-272.

Stigson, P., Hansson, A., Lind, M., 2012. Obstacles for CCS deployment: an analysis of discrepancies of perceptions. Mitigation and Adaptation Strategies for Global Change 17, 601-619.

Strachan, N., Hoefnagels, R., Ramirez, A., van den Broek, M., Fidje, A., Espegren, K., Seljom, P., Blesl, M., Kober, T., Grohnheit, P.E., 2011. CCS in the North Sea region: a comparison on the cost-effectiveness of storing CO_2 in the Utsira formation at regional and national scales. International Journal of Greenhouse Gas Control 5, 1517-1532.

Šúri, M., Huld, T.A., Dunlop, E.D., Ossenbrink, H.A., 2007. Potential of solar electricity generation in the European Union member states and candidate countries. Solar Energy 81, 1295-1305.

Theil, H., 1954. Econometric models and welfare maximization. Weltwirtschaftliches Archiv 72, 60-83.

Theil, H., 1956. On the theory of economic policy. American Economic Review 46, 360-366.

Theil, H., 1964. Optimal decision rules for government and industry. North Holland Publishing Company, Amsterdam.

Tinbergen, J., 1952. On the theory of economic policy. North Holland Publishing Company, Amsterdam.

Tinbergen, J., 1956. Economic policies, principles and design. North Holland Publishing Company, Amsterdam.

Traber, T., Kemfert, C., 2009. Impacts of the German support for renewable energy on electricity prices, emissions and firms. The Energy Journal 30, 155-178.

Traber, T., Kemfert, C., 2012. German nuclear phase out policy – effects on European wholesale prices, emission prices, conventional power plant investments and electricity trade. Discussion Paper. Deutsches Institut für Wirtschaftsforschung.

Train, K., 1985. Discount rates in consumers' energy-related decision: a review of the literature. Energy 10, 1243-1253.

UB, 2014. Kraftwerke in Deutschland. Umweltbundesamt. Retrieved on 20-01-2014. http://www.umweltbundesamt.de/dokument/datenbank-kraftwerke-in-deutschland

UNDP, 2013. Derisking renewable energy investment. New York.

US EIA, 2010. Updated capital cost estimates for electricity generation plants. Washington DC.

US EIA, 2013. Updated capital cost estimates for utility scale electricity generating plants. Washington DC.

US DOE, 2014. Europe Brent crude oil spot price. US Department of Energy. http://www.eia.gov/dnav/pet/hist_xls/RBRTEd.xls.

Vithayasrichareon, P., MacGill, I.F., 2012. A Monte-Carlo based decision-support tool for assessing generation portfolios in future carbon constrained electricity industries. Energy Policy 41, 374-392.

Weigt, H., Delarue, E., Ellerman, D., 2012. CO_2 abatement from renewable energy injections in the German electricity sector. CEEPR WP 2012-003.

Wildavsky, A., 1979. The art and craft of policy analysis. Macmillan Press, London.

Woerdman, E., Couwenberg, O., Nentjes, A., 2009. Energy prices and emissions trading: windfall profits from grandfathering? European Journal of Law and Economics 28, 185-202.

World Bank, 2014. State and trends of carbon pricing. Washington DC, USA.

Wright, T.P., 1936. Factors affecting the costs of airplanes. Journal of the Aeronautical Sciences 3, 122-128.

7. ABBREVIATIONS

3E	Efficacy, Effectiveness and Efficiency (relates to the 3E method (Appraise, 2014))
All.	Allowances
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CHP	Combined Heat and Power
CRC	Carbon Reduction Commitment (UK law to stimulate energy efficiency measures)
Diff.	Difference
EEG	Erneuerbare Energien Gezets (legislation on the feed-in tariff scheme in Germany)
EIs	External Instruments (parallel instruments EU ETS sectors other than the German power sector)
EOR	Enhanced Oil Recovery (CCS application in which injected CO_2 is used to recover oil from a reservoir)
ETSM	Emissions Trading Scheme Module
EU	European Union
EU ETS	European Union Emissions Trading Scheme
FCPI	Fundamental Carbon Price Indicator
FITs	Feed-in tariffs
GBM	Geometric Brownian Motion
GHG	Greenhouse gasses
GJ	Gigajoule
GPSM	German Power Sector Module
GW	Gigawatt (equal to a 1,000 megawatt)
GWh	Gigawatt hour (equal to a 1,000 megawatt hour)
kW	Kilowatt (equal to 1,000 watt)
kWh	Kilowatt hour (equal to a 1,000 watt hour)
m	Meter
M	Mean output value (see tables in the results section)
MEE	Meerjarenafspraak Energie-efficientie (Dutch agreement between government and industry on energy efficiency measures)
$MtCO_2$	Megatonne of CO_2 (equal to a 1,000,000 metric tonnes of CO_2)
MW	Megawatt
MWh	Megawatt hour (equal to the generation of one MW for the duration of one hour)
NAP	National Allocation Plan
NCP	Non Compliance Penalty
NER	New Entrants Reserve
NPO	Nuclear Phase Out
NPV	Net Present Value
P10	10th percentile (10% of all observations are lower than the reported value)
P90	90th percentile (90% of all observations are lower than the reported value)
PIMA Sol	Plan de Impulso al Medio Ambiente en el Sector hotelero (Spanish law to stimulate GHG reduction)
pdf	Probability Distribution Function
RGGI	Regional Greenhouse Gas Initiative
ROC	Renewable Obligation Certificates
SDE+	Stimulering Duurzame Energieproductie (Dutch measure to stimulate renewable energy)
Stdev	Standard Deviation
T1	Type 1 instruments
T2	Type 2 instruments
tCO_2	Tonne of CO_2
UNFCCC	United National Framework Convention on Climate Change
USA	United Stated of America
W	Watt
Yr	Year

8. VARIABLES AND PARAMETERS

	Parameter	**Type**	**Dimension**	**Equation**
A				
AD	Demand for EU ETS emission allowances	Exogenous / Endogenous	$MtCO_2$	4.49
AR	Annual reduction of the EU ETS emission allowance cap	Exogenous	$MtCO_2$	2.1
AS	Supply of EU ETS emission allowances	Exogenous	$MtCO_2$	2.1
C				
c_{max}	Upper bound to the Clearness Index	Exogenous	#	4.8
C	Cap of EU ETS emission allowances	Exogenous / Endogenous	$MtCO_2$	2.1
CAP	Generation capacity	Exogenous / Endogenous	MW	4.4
$CAPF$	Capacity factor	Exogenous	%/100	4.5
CI	Carbon Intensity	Exogenous	tCO_2/MWh	4.14
CF	Forecasted costs	Endogenous	€/MW	4.26
CT	Construction time	Exogenous	# in years	4.4
D				
d	Help variable to sum the electricity production of FIT-based production capacity over all years in which FIT-based production has been commissioned	Endogenous	#	4.35
D	Demand for electricity in a time slice (ts)	Endogenous	MWh	4.3
DC	Deployed capacity of abatement potential	Endogenous	tCO_2	2.10
$Dexp$	Assumed exports of electricity (for calculation of the EEG apportionment)	Exogenous	MWh	4.46
$Dloss$	Network losses and unregistered use of electricity	Exogenous	MWh	4.46
$Down$	Electricity use by the electricity sector itself	Exogenous	MWh	4.46
$Dpriv$	Electricity demanded by privileged sectors (= sectors that face strong international competition)	Exogenous	MWh	4.46
E				
e	Mathematical constant ≈ 2.71828	Exogenous	-	4.25
E	Spot electricity price (Wholesale)	Endogenous	€/MWh	4.15
EEG	EEG Apportionment	Endogenous	€/MWh	4.45
EC	Cost of emitting CO_2	Endogenous	€/MWh	4.16
EF	Forecast of the electricity price	Endogenous	€/MWh	4.28
EG	Growth in the emission level in the rest of Europe	Exogenous	%/100	4.49
ELG	Growth in electricity demand in Germany	Exogenous	%/100	4.1
EM	Emission level in the German power sector	Endogenous	$MtCO_2$	4.14
EPF	Expected production factor	Endogenous	MWh/MW	4.28
F				
FC	Cost of fuel use	Endogenous	€/MWh	4.16
$FCPI$	Fundamental Carbon Price Indicator	Endogenous	€/tCO_2	4.17
FIT	FIT-tariff	Exogenous	€/MWh	4.32
$FITEPF$	Expected production factor of FIT-based capacity	Endogenous	MWh/MW	4.32
$FITEXP$	Total FIT expenses: the total amount of money that is transferred to FIT-based operators in a given year	Endogenous	€	4.47
FITP	Total production level of all FIT-based production capacity	Endogenous	MWh	4.35
$FITREV$	Total FIT revenues: the total amount of money that network operators earn by selling the electricity that was produced by FIT-based production capacity in the market place.	Endogenous	€	4.48
FOC	Fixed operating expenses (are incurred even if no electricity is produced)	Exogenous	€/MW	4.27
$FOR1$	Electricity that is sold for delivery one year ahead	Endogenous	MWh	4.24
$FOR2$	Electricity that is sold for delivery two years ahead	Endogenous	MWh	4.24
$FORP$	Electricity that is produced based on previously negotiated forward contracts	Endogenous	MWh	4.10
FP	Fuel price	Exogenous / Endogenous	€/GJ	4.18
G				
g	Mean clearness index	Exogenous	#	4.8

GAS	Gross allowance surplus	Endogenous	MtCO$_2$	2.4
H				
h	hour	Exogenous	#	4.5
I				
i	Index for electricity generation technologies in the German power sector	Exogenous	#	4.4
$import$	Imports of electricity	Endogenous	MWh	4.13
$INER$	Issued allowances from the New Entrants Reserve	Exogenous	MtCO$_2$	2.3
INV	Investments	Exogenous / Endogenous	MW	4.4
K				
k	Index for CO$_2$ abatement technologies in ETS sectors	Exogenous	#	2.11
L				
L	Saturation limit	Exogenous	MWh	4.25
LF	Load factor	Exogenous	%/100	4.3
LT	Life time of a technology	Exogenous	# in years	4.26
M				
MAC	Marginal abatement costs	Exogenous	€/tCO$_2$	2.11
MC	Marginal production costs	Endogenous	€/MWh	4.12.1
$MC2$	Forecast of the marginal production costs two years ahead	Endogenous	€/MWh	4.20.1
N				
n	Number of CO$_2$ abatement technologies in the EU ETS model	Exogenous	#	2.13
NAS	Net Allowance Surplus	Endogenous	MtCO$_2$	2.6.1
NCP	Non Compliance Penalty	Exogenous / Endogenous	€	2.7
NE	Emissions by new entrants into the EU ETS	Exogenous	MtCO$_2$	2.3
O				
OC	Other operating costs	Endogenous	€/MWh	4.16
P				
P	Spot production	Endogenous	MWh	4.12.1
$P1$	Forecast of the spot production level one years ahead	Endogenous	MWh	4.23
$P2$	Forecast of the spot production level two years ahead	Endogenous	MWh	4.20.1
PF	Production factor: maximum production in MWh per time slice for 1 MW of production capacity	Endogenous	MWh/MW per ts	4.5
R				
r	Discount rate	Exogenous	%/100	4.26
RD	Residual demand	Endogenous	MtCO$_2$	4.49
RE	Retail electricity price	Endogenous	€/MWh	4.2
RET	Retired capacity	Exogenous	MW	4.4
RF	Forecasted revenue	Endogenous	€/MW	4.26
RFFIT	Forecasted revenue of FIT-based production capacity	Endogenous	€/MW	4.32
S				
s	Season	Exogenous	#	4.18
SD	Spot demand for electricity	Endogenous	MWh	4.10
SP	Available production capacity for spot production	Endogenous	MWh	4.11
T				
t	Year	Exogenous	#	4.1
$T1$	Abatement via Type 1 parallel instruments	Exogenous	MtCO$_2$	4.49
$T2$	Abatement via Type 2 parallel instruments	Exogenous	MtCO$_2$	4.49
TA	Total abatement of CO$_2$ via all EU ETS sectors (in Chapter 4 covering all EU ETS sectors except for the German power sector)	Endogenous	MtCO$_2$	2.13
TD	Total demand for electricity	Exogenous / Endogenous	MWh	4.1
TDC	Cumulative deployed capacity of abatement technology in year t since 2008	Endogenous	MtCO$_2$	2.12
TEC	Cost savings that are achieved via technological experience curve effects	Exogenous	%/100	4.51
$TDEEG$	Total demand for electricity by consumers that are obliged to pay the EEG apportionment	Endogenous	MWh	4.46
ts	Time Slice	Exogenous	#	-
U				
UBA	Used Banked Allowances from the stock of Banked Allowances (BA)	Endogenous	MtCO$_2$	2.5.2.
W				

W	Wiener process sample from a normal distribution with mean 0 and standard deviation 1	Exogenous	#	4.19
Y				
ya	Years ahead of t, index used for forecasting cash flows	Endogenous	#	4.20.3
Other				
300	Captures emission allowances from the NER300 reserve	Exogenous	#	2.1
ε	Scalar that accounts for the fact that part of the EU ETS allowance cap is reserved in the New Entrants Reserve between 2008 and 2020.	Exogenous	#	2.1
ϵ	Dummy variable that accounts for the fact the operators only receive a FIT-tariff over the first 20 operational years	Endogenous	#	4.32
ω	Weibull distribution	Exogenous	-	4.6
β	Burn rate	Exogenous	GJ/MWh	4.18
λ	Scale parameter of a Weibull distribution	Exogenous	#	4.6
κ	Shape parameter of a Weibull distribution	Exogenous	#	4.6
∂	Scale parameter of the gamma distribution	Exogenous	#	4.8
ν	Shape parameter of a gamma distribution	Exogenous	#	4.8
μ	Average historical growth rate of a fuel price	Exogenous	%/100	4.19
σ	Historical standard deviation of the fuel price growth rate	Exogenous	%/100	4.19
ϙ	Dummy variable that indicates whether certain investments are FIT-based production capacity or regular production capacity	Endogenous	#	4.34.2
ϖ	Dummy variable that indicated whether producing electricity is profitable for FIT-based production capacity that was commissioned in a particular year	Endogenous	#	4.35

9. APPENDIX

Figure 9.1: Retirement of 2008 generation capacity

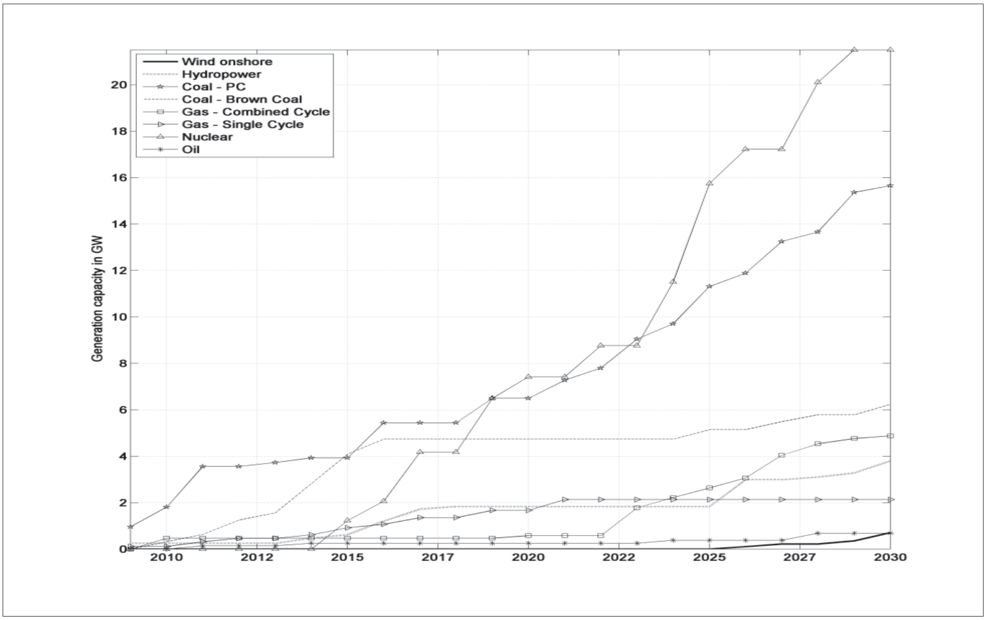

Figure 9.2: Determination of capacity factor of wind energy

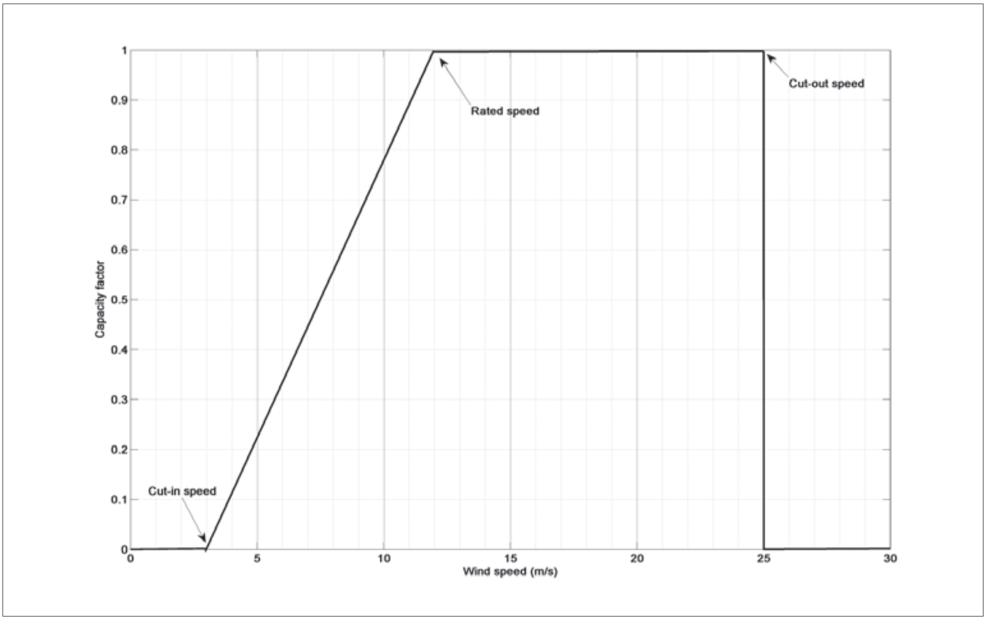

Figure 9.3: Cumulative distribution functions of the clearness index

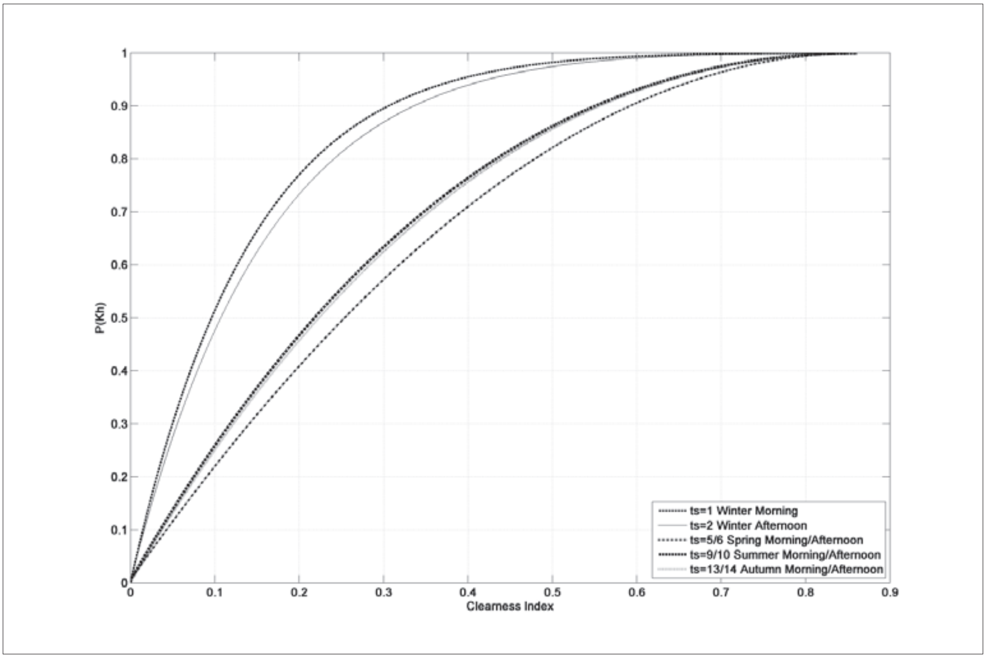

Figure 9.4: Example of generated price indexes

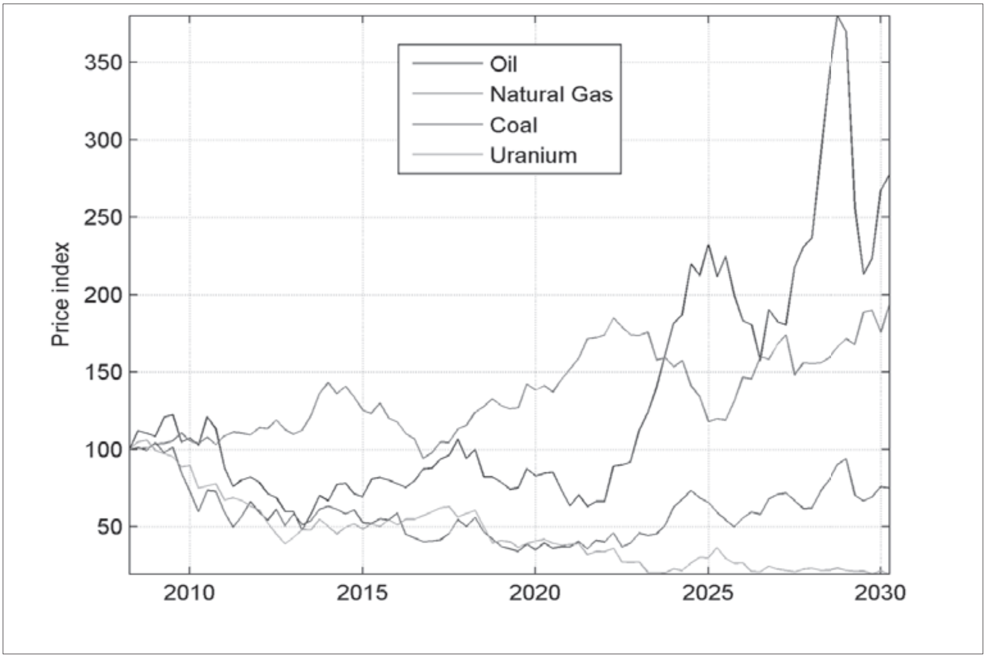

Figure 9.5: Confidence intervals of generated price indexes (2,000 model trails)

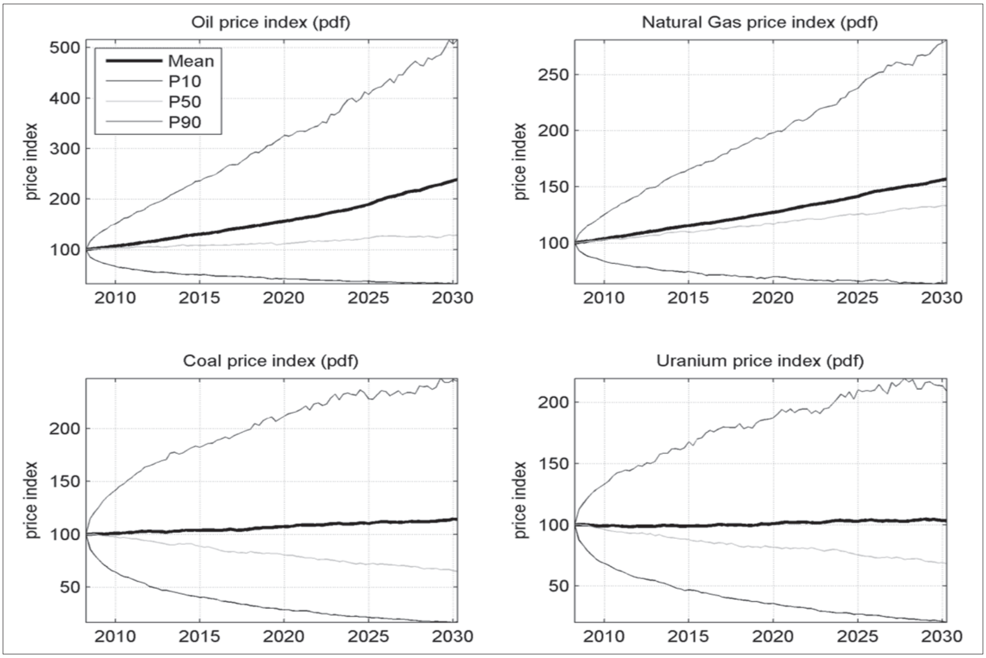

Figure 9.6: Relationship between profitability and investments (upper limit =2,821 MW)

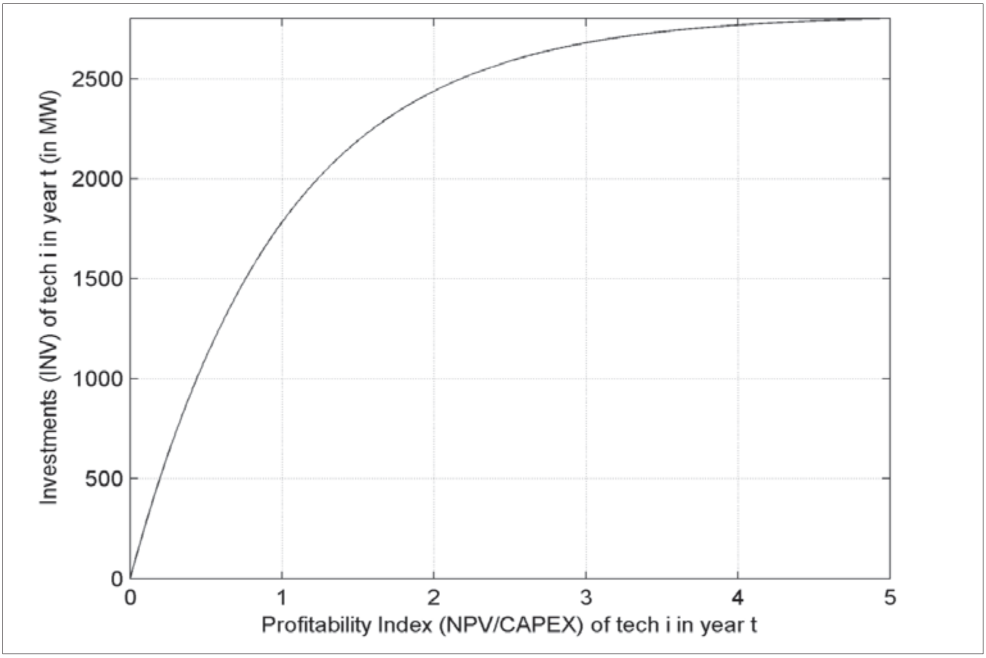

Table 9.1: Input variables per time slice for the GPSM

#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11
Time slice			Load Factor (rounded)	Wind Speed Distribution Onshore (i=1)		Wind Speed Distribution Offshore (i=2)		Clearness Index Distribution		
ts	*Season* (s)	*Part of Day*	LF_{ts}	λ_{ts}^{i}	κ_{ts}^{i}	λ_{ts}^{i}	κ_{ts}^{i}	g_{ts}	ν_{ts}	∂_{ts}
1	Winter (1)	Morning	0.070	6.85	1.77	10.66	2.26	0.11	-5.6606	7.1018
2		Afternoon	0.072	7.33	1.99	10.71	2.24	0.13	-4.8533	6.3432
3		Evening	0.067	5.85	1.38	10.73	2.32	0.00	-	-
4		Night	0.052	5.76	1.49	10.59	2.33	0.00	-	-
5	Spring (2)	Morning	0.067	7.11	2.22	9.57	2.33	0.29	0.0483	2.2827
6		Afternoon	0.068	7.44	2.37	10.04	2.45	0.29	0.0483	2.2827
7		Evening	0.060	4.56	1.45	9.51	2.39	0.01	-	-
8		Night	0.046	4.46	1.40	9.48	2.44	0.01	-	-
9	Summer (3)	Morning	0.066	6.46	2.11	9.50	2.18	0.26	-0.6993	2.8035
10		Afternoon	0.068	6.49	2.03	9.63	2.24	0.26	-0.6993	2.8035
11		Evening	0.060	3.50	0.93	9.01	2.12	0.01	-	-
12		Night	0.046	3.58	0.93	9.41	2.43	0.01	-	-
13	Autumn (4)	Morning	0.070	7.05	1.63	11.80	2.52	0.10	-6.0838	7.5039
14		Afternoon	0.072	6.93	1.72	11.63	2.36	0.10	-6.0838	7.5039
15		Evening	0.066	6.07	1.35	11.85	2.65	0.00	-	-
16		Night	0.051	6.07	1.44	11.71	2.67	0.00	-	-
Source of load factor: ENTSOE (2014) based on hourly load values for Germany over the year 2013. Source for wind speed distributions: KNMI (2014) from Huibertsgat (offshore) and Volkel (onshore) stations from 2011 to 2013. Source for capacity factor of solar power: PVGIS (2012) Latitude 50−37'30" North, Longitude 10−1'10" East. Global average irradiance data with 15 minute interval, assuming a 35° inclined plane, oriented to the south.										

Table 9.2: Technology characteristics (non-financial)

#	Technology name	Fuel	Constr-uction Time	Capacity in 2008 MW	Life time	Available from	Capacity Factor	CO_2 intensity CO_2/MWh	Burn Rate (rnd.) GJ/MWh
i			CT^i	CAP^i	LT^i	NL = No Limit	$CAPF^i$	CI^i	β^i
1	Wind onshore	Wind	1	23,815	25	NL	-	0	0.00
2	Wind offshore	Wind	3	0	25	NL	-	0	0.00
3	Solar PV - Commercial	Solar	0	918	25	NL	-	0	0.00
4	CSP	Solar	1	0	20	NL	-	0	0.00
5	Hydro	Water	4	10,059	50	NL	0.25	0	0.00
6	Ocean	Wave	1	0	20	2020	0.5	0	0.00
7	Geothermal	Heat	2	3	30	NL	0.3	0	0.00
8	Biomass - CHP	Biomass	4	991	30	NL	0.3	0	10.00
9	Biomass - CHP	Biomass	4	0	30	2015	0.3	0	12.93
10	Biomass - dedicated	Biomass	4	991	40	NL	0.3	0	10.90
11	Biomass - dedicated	Biomass	4	0	40	2015	0.3	0	9.64
12	Biogas	Biogas	4	1,455	40	NL	0.25	0.4	11.61
13	Coal	Black Coal	4	29,648	40	NL	0.95	0.86	8.70
14	Coal	Brown Coal	4	22,360	40	NL	0.95	0.99	14.40
15	Gas - Combined Cycle	Gas	3	17,976	30	NL	0.95	0.4	6.42
16	Gas - Single Cycle	Gas	2	4,778	25	NL	0.95	0.4	9.47
17	Nuclear	Nuclear	4	21,587	40	NL	0.95	0.016	61.66
18	Oil	Oil	3	5,350	30	NL	0.95	0.67	11.25
19	CCS Coal - IGCC	Black Coal	4	0	40	2025	0.95	0.09	10.74
20	CCS Coal - Oxyfuel	Black Coal	4	0	40	2025	0.95	0.09	9.47
21	CCS Coal - PC	Black Coal	4	0	40	2025	0.95	0.09	10.00
22	CCS Gas - Combined Cycle	Gas	3	0	30	2025	0.95	0.04	7.82

Sources for capacity in 2008: AGEB (2013a), BUNR (2013). Sources provide totals for Solar PV, Biomass and Gas. Multiple technologies fall within each of these classes. The shares of individual techs within a class is based on own assumptions: Solar PV Commercial (0.15) vs Decentralized (0.85); Biomass CHP (0.5) vs dedicated (0.5); Gas Combined Cycle (0.79) vs Single Cycle (0.21).

Table 9.3: Technology characteristics (financial)

#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Tech	Technology name	Other operating costs (€/MWh)	Fixed operating costs (€/MWh)	Capital costs (€/MW)	Learning Rate		Saturation limit (MW)	FIT-capacity in 2008 (MW)	Average FIT of FIT-capacity in 2008 (€/MWh)
i		OC^i	FOC^i	$CAPEX^i$	BAU	Sen	L^i		
1	Wind onshore	1.81	8,171	1,562,083	0%	2%	10,000	22,794	88
2	Wind offshore	4.40	34,218	3,704,558	0%	3%	1,000	0	150
3	Solar PV - Commercial	0.00	14,604	1,737,858	0%	2%	20,000	6,120	502
4	CSP	0.00	0	4,519,831	0%	2%	7	0	0
5	Hydro	0.00	11,874	1,647,057	0%	1%	250	1,270	76
6	Ocean	7.38	0	6,299,509	0%	3%	7	0	0
7	Geothermal	4.08	0	2,738,711	0%	2%	750	3	150
8	Biomass - CHP	-13.94	187,923	4,402,246	0%	2%	1,000	959	142
9	Biomass - CHP	-20.99	124,026	4,166,863	0%	3%	1,000	0	0
10	Biomass - dedicated	1.00	155,439	2,637,706	0%	2%	1,000	959	142
11	Biomass - dedicated	4.92	48,034	2,979,143	0%	3%	1,000	0	0
12	Biogas	0.00	231	2,551	0%	2%	1,800	638	71
13	Coal	0.53	13,582	1,349,815	0%	1%	2,000	0	0
14	Coal	3.78	22,698	1,556,798	0%	1%	2,000	0	0
15	Gas - Combined Cycle	0.40	14,401	694,351	0%	1%	2,000	0	0
16	Gas - Single Cycle	0.89	0	415,510	0%	1%	2,000	0	0
17	Nuclear	0.40	74,220	4,119,107	0%	1%	1,000	0	0
18	Oil	3.78	22,698	1,287,529	0%	1%	700	0	0
19	CCS Coal - IGCC	12.69	71,854	2,498,149	0%	3%	1,000	0	0
20	CCS Coal - Oxyfuel	11.16	72,838	3,150,247	0%	3%	1,000	0	0
21	CCS Coal - PC	13.51	60,042	2,633,490	0%	3%	1,000	0	0
22	CCS Gas - Combined Cycle	5,34	40,848	1,330,279	0%	3%	1,000	0	0

Sources for cost parameters: averaged over estimates from the following sources: IPCC 2005; IEA/NEA, 2010; US EIA, 2010, 2013; Black & Veatch, 2012; DEA, 2012; EDF, 2012; IRENA, 2012, 2013; JRC, 2012, 2013; NREL, 2012; Schmidt *et al.,* 2012; IEA, 2013; IEA-RETD, 2013; UNDP, 2013. Learning rates are assumed to be 0% in the Base Case Scenario. Sources for calculation of saturation level: BUNR, 2013; BWT, 2013. Assumed saturation levels for CSP, Ocean, Geothermal and CCS-based technologies. CCS-based technologies are assigned the saturation limit of the same technology without CCS. Low levels are assigned to CSP and Ocean because of limited technical scope for these technologies. Geothermal technology is assigned the saturation limit of Biomass. Source for FIT-capacity in 2008: Bundesnetzagentur, 2010.

Table 9.4: Fuel prices

#1	*#2*	*#3*	*#4*	*#5*	*#6*	*#7*	*#8*	*#9*
	Assumptions		Empirical standard dev. of quarterly returns (based on historical data from 2009-Q3 to 2014-Q1)	Empirical correlations of quarterly returns (based on historical data from 2009-Q3 to 2014-Q1)				
Fuel	*€/GJ in* $t = 2008$ $s = 1$	*Assumed Mean Seasonal growth*	σ	*Black Coal*	*Brown coal*	*Gas*	*Uranium*	*Oil*
Biomass	8.00	0.50%	-	-	-	-	-	-
Biogas	5.38	0.50%	-	-	-	-	-	-
Black Coal	3.39	0.14%	0.1121	1	-	-	-	-
Brown Coal	1.09	0.14%	0.1121	1	1	-	-	-
Gas	7.17	0.50%	0.0601	0.2503	0.2503	1	-	-
Uranium	0.00135	0.00%	0.0953	0.3724	0.3724	0.2660	1	-
Oil	13.24	1.00%	0.1169	0.6331	0.6331	0.0511	0.3314	1
Sources for calculating standard deviations and correlations: Australian thermal coal and Russian Natural Gas border price in Germany (IMF, 2014), Uranium u3o8 Nuexco spot (IndexMundi, 2014), Europe Brent oil spot price (US DOE, 2014). Calculations based on historical data from 2009-Q3 to 2014-Q1.								

Table 9.5: Available nuclear generation capacity (in MW) under NPO regulation

	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22
NPO	21,587	21,587	21,587	21,587	12,000	12,000	12,000	12,000	10,800	10,800	9,500	9,500	8,100	4,000	4,000

Table 9.6: Demand between 2008-2030 that is exempt from the EEG apportionment (in TWh)

	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
$Down_t$	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35
$Dpriv_t$	72	75	78	81	84	87	90	93	96	99	102	105	108	111	114	117	120	123	126	129	132	135	138
$Dexp_t$	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
$Dloss_t$	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
Source: own assumptions based on current data (and projections) from AGEB (2013b) and Henkel and Lenck (2013).																							

10. SAMENVATTING

In 2005 trad het Europese emissiehandelssysteem (afgekort EU ETS) in werking. De EU beoogt met dit systeem enerzijds de collectieve emissies van de installaties die onder het stelsel vallen te beheersen en anderzijds om investeringen te stimuleren Dit proefschrift gaat vooral in op de vraag waarom de EU tot dusverre niet overtuigend in dit tweede doel lijkt te slagen. We onderzoeken daartoe in hoeverre het ontwerp van het EU ETS zelf - in combinatie met de diverse beleidsmaatregelen buiten het stelsel - kan verklaren waarom.

Het EU ETS stelt een jaarlijkse limiet aan de individuele en dus gezamenlijke CO_2-uitstoot van ca. 12.000 energie-intensieve installaties, welke gezamenlijk verantwoordelijk zijn voor iets minder dan de helft van alle CO_2-emissies binnen de EU, en vermindert deze limiet jaarlijks met een vast percentage. De EU dwingt bedrijven om te voldoen aan deze limiet door ieder jaar, in lijn met de gestelde limiet, een beperkt aantal emissiecertificaten in omloop te brengen. Bedrijven zijn vervolgens verplicht om één certificaat (officieel afgekort EUA, ofwel European Union Allowance) te hebben voor elke ton CO_2 die zij uitstoten. Heeft een bedrijf dat valt onder het EU ETS geen certificaat, maar stoot het toch CO_2 uit, dan ontvangt het een hoge boete. Sinds 2005 heeft de overheid het grootste gedeelte van deze certificaten gratis aan bedrijven verstrekt, maar in toenemende mate zullen bedrijven certificaten moeten inkopen op veilingen. Daarnaast kunnen bedrijven onderling de certificaten aan elkaar kopen en verkopen. Omdat deze handel voornamelijk via beurzen verloopt, is er een marktprijs voor EUAs. Door het totale aantal EUAs elk jaar naar beneden bij te stellen, beoogt men om certificaten schaarser te maken, de marktprijs omhoog te stuwen en daarmee bedrijven aan te zetten om te investeren in technologie met een lage (of geen) CO_2-uitstoot.

De EU streeft ernaar dat het EU ETS op structurele basis investeringen weet te prikkelen bij Europese industrie omdat op die manier de Europese emissiereductiedoelstelling (-40% in 2030 in vergelijking met 1990) op een goedkopere manier kan worden behaald. Immers, als er op structurele basis vraag is naar ‘schone’ technologieën (zoals windmolens, zonnepanelen en isolatiemateriaal), kunnen netwerken van toeleveranciers (zogeheten waardeketens) zich verder ontwikkelen en kunnen er ook leereffecten optreden omdat producenten steeds slimmer leren te werken.

Tot nu toe is het EU ETS nog niet in staat geweest om structureel een prikkel te bieden voor investeringen. De economische crisis die in 2008 begon heeft hierin een grote rol gespeeld: het productieniveau van de Europese industrie daalde sterk waardoor de CO_2-emissies in 2009 meer dan 11% lager waren dan het emissieniveau in 2008. Hierdoor daalde zowel de vraag naar emissierechten als de marktprijs voor EUAs. Waar de prijs voor EUAs midden 2008 nog boven de 30 euro stond, daalde de prijs begin 2013 tot onder de 3 euro. Doordat emissierechten goedkoper zijn geworden, zijn investeringen in technologie met een lage CO_2-uitstoot logischerwijs ook minder interessant geworden.

De grote vraag is daarom of het EU ETS in de toekomst wel in staat zal zijn om op structurele basis een investeringsprikkel te bieden aan de Europese industrie, en welke maatregelen hiervoor eventueel noodzakelijk zijn. In dit proefschrift geven we een antwoord op deze vragen.

Hoofdstuk 1 introduceert de onderzoeksvragen die in dit proefschrift worden behandeld. In Hoofdstukken 2, 3 en 4 worden de onderzoeken beschreven, en in Hoofdstuk 5 volgt een conclusie en epiloog. De onderzoeksvragen die in Hoofdstukken 2, 3, en 4 worden behandeld bouwen op twee deelterreinen in de literatuur:

1) In Hoofdstuk 2 kijken we naar de mate waarin potentiele investeerders bloot staat aan investeringsonzekerheid vanwege de marktgedreven, en dus onzekere, prijs van EU ETS emissierechten. Specifiek kijken we naar potentiele investeerders in ondergrondse CO_2-opslag (afgekort CCS). We doen dit omdat het grote technische potentieel van CCS om CO_2 te reduceren vaak van doorslaggevende betekenis wordt geacht om de verregaande emissiereductiedoelen te kunnen halen welke de EU voor de periode tot aan 2050 en voor dat jaar hanteert. De EU emissiereductie voor 2050 behelst immers dat de EU dan een zo goed als CO_2-neutrale economie wil hebben gerealiseerd (Pacala and Socolow, 2004; IPCC, 2005; Haszeldine, 2009; EC, 2009b; IEA, 2010; IEA, 2011). Als potentiele investeerders in CCS bloot staan aan te veel CO_2-prijs onzekerheid zullen kritiek geachte investeringen nooit van de grond komen.

2) In Hoofdstuk 3 en 4 richten we ons op de vraag in hoeverre de impact van het EU ETS op investeringsgedrag beïnvloed wordt door andere beleidsinstrumenten. In de afgelopen jaren hebben EU lidstaten vele beleidsinstrumenten geïntroduceerd parallel naast het EU ETS die ook, direct of indirect, het CO_2-emissieniveau beïnvloeden. (EEA, 2011; Lundberg *et al.*, 2012; IPCC, 2013). Voorbeelden zijn subsidies voor de installatie van hernieuwbare elektriciteitsproductiecapaciteit of maatregelen om de energie-efficiëntie van gebouwen te verhogen. Veel van deze instrumenten interacteren op een nadelige manier met het EU ETS (Interact, 2002; Harrison *et al.*, 2005; Sorrell *et al.*, 2009; Alberola, 2014) en kunnen zodoende een verklaring vormen voor een zwakke CO_2-prijs. Tot dusverre is het echter onduidelijk hoe groot de invloed van deze nadelige interacties is geweest.

Hoofdstuk 2 kijkt naar de mate waarin het EU ETS een prikkel kan bieden voor investeringen in een set technologieën die bekend staat als CCS (Carbon Capture and Storage). Wat alle typen CCS gemeen hebben is dat ze CO_2 kunnen afvangen, transporteren en opslaan. CCS kan bijvoorbeeld in de elektriciteits- staal- of cementsector worden toegepast om de CO_2-uitstoot van bestaande en nieuwe installaties met ongeveer 90% te reduceren. De afgevangen CO_2–uitstoot kan vervolgens worden vervoerd (bijvoorbeeld per boot of pijpleiding), om daarna te worden opgeslagen in de diepe ondergrond. Potentiele opslaglocaties zijn, onder andere, lege olie- en gasvelden.

CCS wordt op dit moment nog niet op grote schaal toegepast, maar biedt wel veel potentie. Pacala en Socolow (2004) beargumenteren dat CCS tot $1/7^e$ van de totaal wereldwijd benodigde CO_2-reductie voor haar rekening zou kunnen nemen die nodig is om de ergste consequenties van klimaatverandering te voorkomen. CCS bevindt zich op dit moment nog in een ontwikkelingsstadium, waarbij hoge kosten en onzekerheden de introductie van CCS bemoeilijken. Eén volwaardig CCS-project van industriële omvang vergt al gauw een investering van vele honderden miljoenen euro's of meer, terwijl de doorlooptijd van dergelijke projecten langer kan zijn dan een decennium. Om CCS op een succesvolle manier te introduceren, en leereffecten te behalen, hebben investeerders een voldoende krachtige investeringsprikkel nodig. Daarmee zijn investeringen in CCS een test-case voor het EU ETS. Is het EU ETS in de toekomst in staat om op structurele basis een prikkel te bieden voor de introductie van CCS? In Hoofdstuk 2 bouwen we een stochastisch simulatiemodel van het EU ETS om deze vraag te beantwoorden.

De resultaten laten zien dat het zeer onwaarschijnlijk is dat het EU ETS op structurele wijze een prikkel kan bieden voor de introductie van CCS. De barrière die investeringen tegenhoudt is de onzekerheid over de groei van het emissieniveau in Europa. Als de economische groei tot 2030 relatief hoog is, stijgt het emissieniveau navenant, en zijn er veel investeringen nodig om de CO_2-reductiedoelstelling te kunnen halen. In een dergelijk scenario zou de CO_2-prijs hoog genoeg kunnen worden om de introductie van CCS te ondersteunen. Echter, als de economische groei tot 2030 relatief laag is, hoeft er veel minder geïnvesteerd te worden om diezelfde emissiereductiedoelstelling te halen. Investeerders die vandaag besluiten om te investeren in CCS lopen daarom vaak een omvangrijk risico: de investeerder weet vaak pas geruime tijd na de investeringsbeslissing en planningsfase of de investering het voorziene rendement daadwerkelijk kan leveren. Mede door de omvang van de gerelateerde investeringen en de lange lead times van het CCS ontwikkel- en bouwproces, lijkt het niet aannemelijk dat het EU ETS - met sterk fluctuerende prijzen van de emissierechten en ook op termijn een vrijwel niet te voorspellen prijstrend daarvan - voldoende steun kan bieden om op structurele wijze investeringen in deze technologie te stimuleren.

Daarnaast laten de resultaten zien dat het terugbrengen van het aantal te verstrekken emissierechten de investeringsonzekerheid voor CCS niet zal verminderen. Een lager emissieplafond ondersteunt wel de gemiddelde CO_2-prijs. Echter, één neerwaartse economische schok kan voldoende zijn om een dergelijke opwaarts effect volledig te niet te doen.

Het advies aan beleidsmakers is daarom om niet te focussen op maatregelen die enkel het gemiddelde niveau van de CO_2–prijs ondersteunen. In plaats daarvan zou men zich moeten richten op het terugbrengen van de onzekerheid rondom het gemiddelde. Maatregelen die dit effect sorteren kunnen veel vormen aannemen, maar een voorbeeld is het introduceren van een minimum- en maximumprijs voor emissierechten. Zo kan de CO_2-prijs stabiliseren en een sterkere prikkel bieden voor investeerders, ook op de langere termijn.

Hoofdstuk 3 en 4 introduceren de lezer met beleidsinteractie. Beleidsinteractie verwijst naar de interactie die plaatsvindt tussen, enerzijds, het emissiehandelssysteem en anderzijds alle andere instrumenten die door beleidsmakers zijn geïntroduceerd om 1) CO_2 te reduceren, 2) energie efficiëntie te behalen, of 3) om investeringen in hernieuwbare elektriciteit te stimuleren. Omdat deze andere instrumenten parallel naast het EU ETS zijn geïntroduceerd, noemen we deze categorie ‘parallelle instrumenten’ (*i.e.* parallel instruments). Omdat parallelle instrumenten net als een emissiehandelssysteem zorgen voor een lagere CO_2-uitstoot, zijn parallelle instrumenten vaak een substituut voor een emissiehandelssysteem. Als de CO_2–uitstoot van EU ETS sectoren daalt door parallelle instrumenten (bijvoorbeeld middels subsidies voor isolatie en hernieuwbare elektriciteitsopwekking) dan is er minder noodzaak om CO_2 te reduceren via het emissiehandelssysteem om de CO_2-reductiedoelstelling te halen. Dit effect vertaalt zich in een lagere CO_2-prijs: hoe meer CO_2 wordt gereduceerd via parallelle instrumenten, hoe lager de vraag naar emissierechten en hoe lager de CO_2-prijs. Hoewel dit effect al vaak is beschreven in de literatuur (zie bijvoorbeeld Hindsberger *et al.*, 2003; Morthorst, 2003), is het vooralsnog onduidelijk hoe gevoelig het EU ETS hiervoor is.

In Hoofdstuk 3 onderzoeken we onder welke condities het EU ETS ‘overvloedig’ wordt door de introductie van parallelle instrumenten. Het EU ETS is overvloedig als de CO_2-prijs permanent 0 euro is doordat er geen schaarste is op de markt voor emissierechten. Het kwantificeren van de condities waaronder het EU ETS overvloedig wordt helpt om een inzicht te krijgen in de kracht waarmee parallelle instrumenten het EU ETS ondermijnen. Met die informatie kunnen beleidsmakers een betere inschatting maken van de potentiele voor- en nadelen die kleven aan het introduceren van een parallel instrument.

In de analyse maken we onderscheid tussen twee verschillende typen parallelle instrumenten: Type 1 en Type 2 instrumenten. Type 1 instrumenten zijn gedefinieerd als parallelle instrumenten die gericht zijn op bedrijven in EU ETS sectoren en daarmee verbeteringen in de CO_2-intensiteit van de productie teweegbrengen. Een voorbeeld van een Type 1 instrument is een verplichting voor kolencentrales om biomassa bij te stoken. Type 2 instrumenten zijn gedefinieerd als parallelle instrumenten die gericht zijn op niet-EU ETS sectoren, maar desondanks de vraag verlagen naar producten die worden geproduceerd in ETS sectoren. Een voorbeeld van een Type 2 instrument is een subsidie voor de installatie van zonnepanelen op een woonhuis. De installatie van zonnepanelen zorgt ervoor dat de vraag naar elektriciteit van centraal geproduceerde elektriciteit (bijvoorbeeld in een kolen- of gas centrales) daalt. Deze bedrijven halen daardoor een lager productieniveau, stoten minder CO_2 uit, houden emissierechten over en kunnen deze verkopen. Door dit hogere aanbod van emissierechten op de market zorgen ook Type 2 instrumenten voor een lagere CO_2-prijs.

De resultaten laten zien dat Type 2 instrumenten (bijvoorbeeld subsidies voor particulieren voor de installatie van zonnepanelen) een groter neerwaartse effect hebben op de CO_2-prijs dan Type 1 instrumenten (bijvoorbeeld een biomassa bijstookverplichting voor elektriciteitsbedrijven). Dit kan worden verklaard doordat Type 2 instrumenten de verplichting wegnemen bij ETS-bedrijven om CO_2 te reduceren, terwijl deze bedrijven wel al hun CO_2-reductie opties in tact houden. Het ETS bedrijf houdt, met andere woorden, meer vrijheidsgraden over voor de toekomst: het ETS bedrijf kan altijd nog zelf besluiten om biomassa bij te gaan stoken om de CO_2-uitstoot verder te laten dalen. Het feit dat Type 2 instrumenten de vrijheidsgraden van ETS-bedrijven in stand houden, terwijl Type 1 instrumenten dit niet doen, reflecteert zich in een sterker gedeprecieerde CO_2-prijs, doordat toekomstige CO_2-reductie nog steeds relatief goedkoop kan worden behaald en de marginale kosten van de meest efficiënte beschikbare optie de prijs bepalen.

Als de gezamenlijke impact van Type 1 en Type 2 instrumenten groter is dan 40 $MtCO_2$ per jaar, dan is het zeker dat het EU ETS overvloedig zal worden. Als de gezamenlijke impact van Type 1 en Type 2 instrumenten groter dan 20 maar kleiner dan 40 $MtCO_2$ per jaar, dan hangt de toekomst van het EU ETS ook af van de van de economische groei. Hoe lager de economische groei, hoe groter de kans dat het EU ETS overvloedig raakt. Als de impact van Type 1 en Type 2 instrumenten lager is dan 20 $MtCO_2$ per jaar, dan is het onwaarschijnlijk dat het EU ETS overvloedig zal raken. Niettemin kan de CO_2-prijs in dergelijke gevallen wel sterk depreciëren als gevolg van de introductie van parallelle instrumenten.

De genoemde grenswaarden gelden alleen als bedrijven blijven geloven in de goede werking en houdbaarheid van het EU ETS. Zo niet, dan liggen de grenswaarden vermoedelijk significant onder de gerapporteerde 20 en 40 $MtCO_2$ per jaar. Als bedrijven niet gecommitteerd zijn aan het EU ETS zouden ze hun emissierechten kunnen gaan dumpen, terwijl beleidsmakers zouden kunnen aanzetten tot dergelijk gedrag door 1) de toekomst van het EU ETS in twijfel te trekken, 2) maatregelen te nemen met een dergelijk effect, of 3) juist niet maatregelen te nemen op het moment dat daar behoefte aan is.

Als beleidsmakers willen voorkomen dat het EU ETS overvloedig raakt zou men bijvoorbeeld kunnen overwegen om een plafond in te stellen op het gebruik van parallelle instrumenten. Door een plafond in te stellen dat ruim onder de 20 $MtCO_2$ per jaar ligt kan overvloedigheid en daarmee de kans op een extreem lage CO_2-prijs worden verminderd. Hoewel een dergelijk plafond om politieke redenen moeilijk uitvoerbaar zal zijn, zou het wel de toekomst van het EU ETS waarborgen. Tegelijkertijd worden beleidsmakers in Europa zo gedwongen om de voor- en nadelen van verschillende parallelle instrumenten kritisch tegen elkaar af te wegen, alvorens tot introductie over te gaan. Op die manier kan een mix van instrumenten worden ontwikkeld die beter samenhangt, doelgerichter is en waarbij overvloedigheid zo veel mogelijk kan worden voorkomen.

In Hoofdstuk 4 gaan we dieper in op het onderwerp beleidsinteractie. Nadat we in Hoofdstuk 3 hebben vastgesteld dat parallelle instrumenten de potentie hebben om de prestaties van het EU ETS sterk te beïnvloeden, doen we nu een casestudie om beter te begrijpen in welke mate het EU ETS daadwerkelijk wordt beïnvloed door parallelle instrumenten.

De resultaten in Hoofdstuk 4 laten zien dat de combinatie van feed-in tarieven voor hernieuwbare elektriciteitsproductie (afgekort FITs) en de uitfasering van nucleaire productiecapaciteit (NPO) in de Duitse elektriciteitssector de gemiddelde CO_2-prijs met ongeveer €5 laat dalen (ofwel -14% in vergelijking met hetzelfde scenario zonder FITs en NPO). Als we, met een ruwe schatting, alle andere parallelle instrumenten meenemen die in Europa geïntroduceerd zijn, daalt de CO_2-prijs met €20 (ofwel -50% in vergelijking met hetzelfde scenario zonder parallelle instrumenten). De resultaten laten bovendien zien dat overvloedigheid van het EU ETS (en dus een zeer lage prijs voor de emissierechten) een mogelijk resultaat is. Dit zal echter alleen gebeuren wanneer zowel 1) de economische groei langdurig laag is en, 2) de relatieve brandstofprijzen in het voordeel zijn van brandstoffen met een lage CO_2-intensiteit (bijvoorbeeld prijzen waarbij gasgestookte productie van elektriciteit goedkoper is dan productie op basis van (bruin)kolen). Bovenop lage economische groei kunnen dergelijke brandstofprijzen voor verdere uitval van de vraag naar emissierechten leiden.

Op basis van deze resultaten is het advies aan beleidsmakers om de huidige mix aan doelen en instrumenten op het gebied van energie- en klimaatbeleid te heroverwegen. Vereenvoudiging en herkalibratie van doelen en instrumenten kan, zoals in deze studie aangetoond, veel bijdragen aan het versterken van de investeringsprikkel die uit gaat van het EU ETS.

We benadrukken dat de twee onderzochte instrumenten in de Duitse elektriciteitssector (FITs en de NPO) goed in lijn liggen met de doelen waarvoor ze zijn geïntroduceerd. Een NPO is een erg effectieve manier om een volledige uitfasering van nucleaire productiecapaciteit te bewerkstelligen, terwijl ook de introductie van FITs een erg effectieve manier is om investeringen in hernieuwbare productietechnieken te stimuleren. Gegeven dat er politieke doelen zijn gesteld voor nucleaire uitfasering en groei van hernieuwbare productietechnieken in de Duitse elektriciteitssector, kan de keuze voor deze instrumenten daarom eenvoudig worden verdedigd. Voor zover dit representatief is voor alle parallelle instrumenten in Europa, raden we beleidsmakers aan om eerst te focussen op het reduceren van het aantal interacterende beleidsdoelen op het gebied van energie- en klimaatbeleid. Dit advies geldt voor beleidsmakers op alle politieke niveaus: Europees, nationaal, regionaal en lokaal. Als alternatief kunnen parallelle beleidsdoelen worden bijgesteld naar een lager ambitieniveau, zodat negatieve beleidsinteractie enigszins wordt voorkomen. Daarna zouden beleidsmakers moeten focussen op het opnieuw kalibreren van de gekozen instrumenten, zodanig dat negatieve beleidsinteractie met het EU ETS wordt voorkomen.