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# The impact and interaction of emission trading and deployment of renewables regarding $CO_2$ emissions in the European electricity sector

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# Preface

This master thesis is the result of an interesting year of research on electricity generation in Europe. Throughout this year, I received support and help of numerous people without whom this master thesis would not be what it is today. I would like to take some time to thank these persons.

My first word of thanks goes to professor D'haeseleer, promotor of this master thesis. I would like to thank professor D'haeseleer for giving me the opportunity to work on this interesting subject. His feedback and useful comments were highly appreciated and incorporated in this master thesis.

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*Kenneth Van den Bergh*

# Contents

# Abstract

As of 2005, electricity generators in Europe operate under the European Union Emission Trading System (EU ETS). At the same time, European Member States launched support mechanisms to stimulate the deployment of renewable electricity sources (RES-E). Both policy instruments affect $CO_2$ emissions in the electricity sector and the price of European Union Allowances (EUAs). This master thesis quantifies, for the period from 2007 to 2010, the impact of EU ETS and RES-E deployment on $CO_2$ emissions in the Western and Southern European electricity sector and the impact of RES-E deployment on the EUA price. Besides, this master thesis also quantifies the interaction between EU ETS and RES-E support mechanisms with regard to $CO_2$ emissions in the electricity sector, meaning that the impact of one policy instrument depends on the presence of the other instrument.

The first conclusion of this master thesis is that EU ETS and RES-E deployment had a considerable impact on $CO_2$ emissions in the electricity sector. In 2007, 106 million $tCO_2$ or 11 % of historical emissions were not emitted mainly due to RES-E deployment. EU ETS had a negligible impact in 2007 because of the very low EUA price. From 2008 to 2010, the $CO_2$ emission reduction in the electricity sector was respectively 234 million $tCO_2$ or 26 % of historical emissions, 265 million $tCO_2$ or 30 % of historical emissions and 221 million $tCO_2$ or 26 % of historical emissions. In these years, EU ETS and RES-E deployment contributed more or less equally to $CO_2$ emission reductions in the electricity sector.

The second conclusion is that a considerable higher EUA price would have been needed to reduce $CO_2$ emissions in the electricity sector to historical levels in absence of RES-E deployment. In 2007, the EUA price would have to have increased with 15 EUR/$tCO_2$, in 2008 with 46 EUR/$tCO_2$ and in 2010 with 460 EUR/$tCO_2$. In 2009, RES-E deployment was indispensable to achieve historical $CO_2$ emission levels.

The final conclusion addresses interaction between EU ETS and RES-E support mechanisms regarding $CO_2$ emissions in the electricity sector. $CO_2$ displacement from the electricity sector to other ETS sectors due to RES-E deployment is on annual basis on average 7 % higher if EU ETS is in place. Analogously, the impact of the EUA price on $CO_2$ abatement in the electricity sector is on annual basis on average 12 % higher if RES-E deployment is in place.

# Samenvatting

Sinds 2005 opereren elektriciteitsproducenten in Europa onder het *European Union Emission Trading System* (EU ETS). Tegelijkertijd vaardigden alle Europese lidstaten steunmaatregelen uit ter bevordering van productie uit hernieuwbare elektriciteitsbronnen (RES-E). Beide beleidsinstrumenten beïnvloeden de $CO_2$-emissies in de elektriciteitssector en de prijs van *European Union Allowances* (EUAs). Deze thesis kwantificeert, voor de periode van 2007 tot en met 2010, de impact van EU ETS en steun aan RES-E op de $CO_2$-emissies in de West- en Zuid-Europese elektriciteitssector en de impact van steun aan RES-E op de EUA prijs. Daarnaast kwantificeert deze thesis de interactie tussen EU ETS en steun aan RES-E met betrekking op de $CO_2$-emissies in de elektriciteitssector.

De eerste conclusie van deze thesis is dat EU ETS en steun aan RES-E een aanzienlijke impact hadden op de $CO_2$-emissies in de elektriciteitssector. In 2007 werd 106 miljoen $tCO_2$ of 11 % van de historische emissies niet uitgestoten, hoofdzakelijk ten gevolge van steun aan RES-E. De impact van EU ETS was verwaarloosbaar in 2007 door de zeer lage EUA prijs. Van 2008 tot 2010 bedroeg de daling in $CO_2$-emissies respectievelijk 234 miljoen $tCO_2$ of 26 % van de historische emissie, 265 miljoen $tCO_2$ of 30 % van de historische emissies en 221 miljoen $tCO_2$ of 26 % van de historische emissies. In deze periode droegen EU ETS en steun aan RES-E ongeveer in gelijke mate bij tot de daling van de $CO_2$-emissies in de elektriciteitssector.

De tweede conclusie is dat een aanzienlijk hogere EUA prijs nodig zou zijn geweest om de $CO_2$-emissies te beperken tot het historisch niveau zonder steun aan hernieuwbare energie. In 2007 zou de EUA prijs 15 EUR/$tCO_2$ hoger moeten zijn geweest, in 2008 46 EUR/$tCO_2$ en in 2010 460 EUR/$tCO_2$. In 2009 is hernieuwbare productie noodzakelijk om de $CO_2$-emissies te beperken tot het historisch niveau.

De laatste conclusie heeft betrekking op de interactie tussen EU ETS en steun aan RES-E aangaande $CO_2$-emissies in de elektriciteitssector. De verplaatsing van $CO_2$-emissies van de elektriciteitssector naar andere ETS sectoren, veroorzaakt door steun aan RES-E, is op jaarbasis gemiddeld 7 % hoger als EU ETS van kracht is. Analoog is de reductie van $CO_2$-emissies in de elektriciteitssector ten gevolge van EU ETS 12 % hoger als steunmaatregelen voor RES-E van kracht zijn.

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# List of Abbreviations and Symbols

## Abbreviations

| | |
|---|---|
| AT | Austria |
| BE | Belgium |
| CC | Comined Cycle power plants |
| CH | Switzerland |
| CHP | Cogeneration of Heat and Power |
| DE | Germany |
| DK | Denmark |
| ES | Spain |
| EU | European Union |
| EU ETS | European Union's Emission Trading System |
| EU MS | Member State of the European Union |
| EUA | European Union Allowance |
| FIT | Feed-In Tariff |
| FIP | Feed-In Premium |
| FR | France |
| GHG | Greenhouse Gas |
| GT | Gas Turbine power plants |
| IE | Ireland |
| IT | Italy |
| LU | Luxembourg |
| MS12 | Austria, Belgium, Denmark, France, Germany, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain and United Kingdom |
| NL | Netherlands |
| NTC | Net Transfer Capacity |
| PT | Portugal |
| R&D | Research and Development |

| | |
|---|---|
| RoR | Run-of-River power plants |
| RES | Renewable Energy Sources |
| RES-E | Renewable Energy Sources for Electricity |
| TGC | Tradable Green Certificates |
| UK | United Kingdom |

## Scenarios

| | |
|---|---|
| ETS scenario | Emission Trading System scenario with EU ETS in place and RES-E deployment not in place |
| NOPOL scenario | No-policy scenario without RES-E deployment in place and without EU ETS in place |
| OBS scenario | Observed scenario with both RES-E deployment and EU ETS in place |
| RES scenario | Renewable Energy Sources scenario with RES-E deployment in place and EU ETS not in place |

## Assumptions

| | |
|---|---|
| ETS-cap assumption | The electricity sector is subject to a $CO_2$ emission cap imposed by EU ETS. RES-E deployment causes a decrease in the EUA price but does not reduce $CO_2$ emissions in the electricity sector. |
| ETS-price assumption | The electricity sector is subject to an exogenous EUA price imposed by EU ETS. RES-E deployment causes a decrease in $CO_2$ emissions in the electricity sector but does not reduce the EUA price. |

## Sets

| | |
|---|---|
| $i$ | Set of power plant types |
| $j$ | Set of countries |
| $j_2$ | Set of neighboring countries |
| $t$ | Set of time periods |

## Parameters

| | |
|---|---|
| $\eta$ | Rated efficieny of dual storage units |
| $\eta_i$ | Rated efficieny of power plant type $i$ |
| $\mathrm{AF}_{i,j}$ | Availability factor of power plant type $i$ in country $j$ |
| $CO_2$_abatement | $CO_2$ abatement in $tCO_2$ |

| | |
|---|---|
| $CO_2$_cap | $CO_2$ emission cap in $tCO_2$/year |
| $CO_2$_emission$_{i,j,t}$ | $CO_2$ emissions of power plant type $i$ in country $j$ at time $t$ in $tCO_2$/h |
| E | Change in fuel share due to EU ETS in %-points |
| $EF_i$ | Emission factor of power plant type $i$ in $tCO_2/MWh_{prim}$ |
| EUA_price$_t$ | EUA price at time $t$ in EUR/$tCO_2$ |
| $FP_{t,j}$ | Fuel prices in country $j$ at time $t$ in EUR/$MWh_{prim}$ |
| $MC_{i,j,t}$ | Marginal cost of power plant type $i$ in country $j$ at time $t$ in EUR/MWh |
| $NTC_{j,j_2}$ | Net transfer capacity from country $j_2$ to country $j$ in MW |
| $P_{cog,t,j}$ | Power from cogeneration in country $j$ at time $t$ in MWh/h |
| $P_{geo,t,j}$ | Geothermal power in country $j$ at time $t$ in MWh/h |
| $P_{PV,t,j}$ | Photovoltaic power in country $j$ at time $t$ in MWh/h |
| $P_{ss,t,j}$ | Power from single storage in country $j$ at time $t$ in MWh/h |
| $P_{wind,t,j}$ | Wind power in country $j$ at time $t$ in MWh/h |
| R | Change in fuel share due to RES-E deployment in %-points |
| $RF_{i,j}$ | Ramping factor of of power plant type $i$ in country $j$ |
| TC | Cross border transmission cost in EUR/MWh |
| $cap_{i,j,t}$ | Installed capacity of power plant type $i$ in country $j$ at time $t$ in MW |
| cap_dual_storage$_j$ | Installed capacity of dual storage units in country $j$ in MW |
| $cbt_{j,j_2,t}$ | Cross border transmission to country $j$ from country $j_2$ at time $t$ in MWh/h |
| $char_{t,j}$ | Charging rate of dual storage units in country $j$ at time $t$ in MWh/h |
| $demand_{t,j}$ | Electricity demand in country $j$ at time $t$ in MWh/h |
| demand_cor$_{t,j}$ | Corrected electricity demand in country $j$ at time $t$ in MWh/h |
| $gen_{i,j,t}$ | Generation of power plant type $i$ in country $j$ at time $t$ in MWh/h |
| gen_annual$_{i,j}$ | Annual generation of power plant type $i$ in country $j$ in MWh |
| gen_tot | Aggregated electricity generation in MWh |
| $price_{j,t}$ | Electricity price in country $j$ at time $t$ in EUR/MWh |
| pump_energy$_{t,j}$ | Energy content of the dual storage units in country $j$ at time $t$ in MWh |
| pump_energy_max$_{t,j}$ | Maximum energy content of the dual storage units in country $j$ at time $t$ in MWh |
| $rel_{t,j}$ | Releasing rate of dual storage units in country $j$ at time $t$ in MWh/h |

# Chapter 1

# Introduction

## 1.1 Setting the stage

Three decades ago, the European Union started developing a European energy policy with the aim of shaping a deregulated and competitive European electricity market. Two decades ago, the awareness of climate change increased and the aspect of sustainability gained importance, resulting in Europe-wide binding targets for $CO_2$ mitigation and deployment of renewable energy sources (RES).

The European Union aims to reduce greenhouse gas (GHG) emissions with 20 % by 2020 compared to 1990 emission levels, this is equivalent to a 14 % reduction of GHG compared to 2005 emission levels. All large industrial plants, including power plants, are subject to a $CO_2$ emission cap set by the European Union's Emissions Trading System (EU ETS). All industries covered by EU ETS will reduce GHG emissions with 21 % by 2020 compared to 2005 emission levels. Non-ETS sectors are obliged to reduce GHG emissions with 10 % by 2020 compared to 2005 emission levels [20]. At the same time, the European Union pursues a 20 % share of renewable energy sources in final energy consumption by 2020 with a 10 % share of renewable energy specifically in the transport sector. To achieve these targets, the European Union imposes binding targets to each Member State [22]. A 10 % RES share target for the transport sector implies that the electricity sector and/or the heating sector will end up with a RES share above 20 % in 2020.

Launched in 2005, EU ETS is the first and largest cap and trade mechanism in the world for $CO_2$ emissions [15]. It sets a cap on the total amount of $CO_2$ emitted by factories operating under the EU ETS. Within the cap, companies receive, buy or sell emission permits, also referred to as European Union allowances (EUAs). A company can sell allowances and reduce its emissions when the market price for allowances is higher than the abatement cost of the last emitted ton $CO_2$. Vice versa, a company can buy allowances when the EUA market price is lower than its $CO_2$ abatement cost. At the time of writing, EU ETS is in its second phase (2008-2012), covering thousands of installations in 30 countries[1] and in different sectors such as electricity generation and oil refining. Currently, EU ETS covers almost half of the European Union's $CO_2$ emissions and 40 % of the total greenhouse gas emissions in the European Union [21]. The electricity sector represents around 60 % of the emissions covered by the EU ETS [28]. Since the start of the emission trading system, the way emission permits are allocated has changed from 100 % grandfathering[2] to an expected 50 % auctioned permits as of 2013 due to changes in the allocation rules. The aviation sector joined EU ETS in the beginning of 2012 and the scheme will be further expanded to additional industries and additional greenhouse gases as of 2013, when the third trading period will start.

Unlike European $CO_2$ mitigation policy, where electricity generaters are subject to one Europe-wide system[3], European policy with regard to electricity from renewable energy sources (RES-E) is much more diffuse. Each Member State is free to choose its own incentives to stimulate deployment of RES-E. One can distinguish two main types of support mechanisms. The first type covers quantity based mechanisms. In quantity regulation, consumers or suppliers have the obligation to redeem tradable green certificates (TGC) which can be gathered by producing renewable electricity or by purchasing them on the market. The second type of support mechanisms are price regulated mechanisms. In price regulation, a fixed financial payment per unit of renewable energy is awarded to the generator. Feed-in tariffs (FIT) and feed-in premiums (FIP) are price regulated mechanisms. Besides these two types of regulation, policy makers can set up additional measures to make investments in renewables more attractive, e.g. R&D grants, fiscal incentives and tendering [11].

The electricity market, EU ETS and RES-E deployment are linked in multiple ways. Figure 1.1 gives a schematic overview of the interdependencies. Both EU ETS and RES-E deployment influence $CO_2$ emissions from electricity generators. EU ETS caps the overall $CO_2$ emission from all ETS sectors, including the electricity sector, and puts a price on the emission of $CO_2$. The generation of $CO_2$ free electricity from supported renewable electricity sources reduces $CO_2$ emissions needed to fulfill electricity demand. As aggregated $CO_2$ emissions are capped, RES-E generation does not cause a $CO_2$ emission reduction but it displaces $CO_2$ emissions within the ETS sectors.
The reduction in demand for EUAs due to RES-E deployment translates into a lower EUA price. The other way around, EU ETS reduces the need for RES-E support mechanisms. By putting a price on $CO_2$ emissions, EU ETS narrows the cost gap between renewable technologies and conventional technologies. The latter effect is however much smaller than the first effect.
EU ETS increases electricity prices as generators take the $CO_2$ emission cost into account in the marginal electricity generation cost, regardless if the allowances were grandfathered or auctioned. Allowances have a market value and thus represent an opportunity cost for the generator. The effect of RES-E deployment on electricity

[1] EU-27, Iceland, Liechtenstein and Norway.
[2] Grandfathering is the free allocation of EUAs based on historical emission data.
[3] National fossil fuel taxes are not considered as a policy instrument to reduce $CO_2$ emissions.

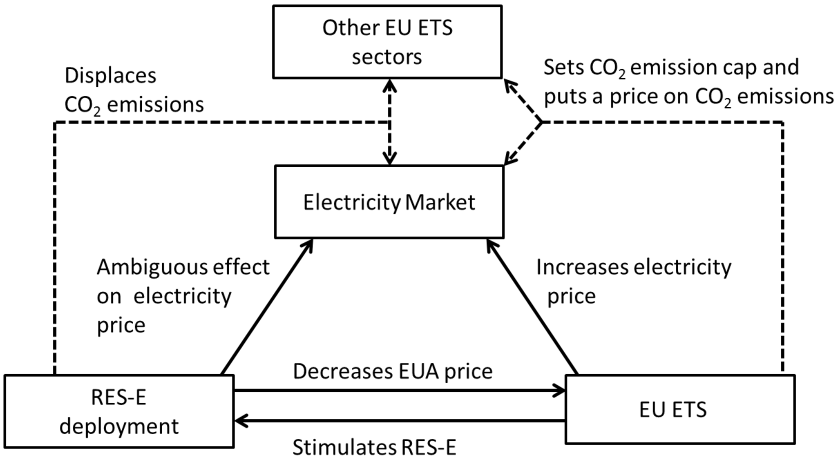



FIGURE 1.1: Schematic presentation of the interdependencies between the European electricity market, EU ETS and RES-E deployment. Solid lines indicate price interdependencies, dotted lines indicate $CO_2$ interdependencies. Figure results from elaboration of the author based on del Río González [8].

prices is ambiguous. On the one hand, wholesale electricity prices are lowered because of the low marginal generation cost of renewable power plants. On the other hand, the cost of RES-E support schemes is often passed on to the customer in the form of higher tariffs. RES-E deployment also influences electricity prices indirectly by decreasing the EUA price. Hence RES-E causes a decrease in wholesale electricity price but the effect on the retail price is less clear.

This master thesis focuses on $CO_2$ emission interdependencies and the EUA price decrease caused by RES-E deployment.

## 1.2 Thesis objectives and motivation

EU ETS and RES-E deployment are both important pillars of the European policy regarding electricity generation. The impact of both policy instruments on the $CO_2$ emissions in the European electricity sector and the EUA price has been repeatedly discussed in literature from a theoretical point of view. Today, after some years of electricity generation under both policy instruments, it is imperative to assess the effective impact of EU ETS and RES-E deployment.

This master thesis aims to quantify, for the period from 2007 to 2010, the impact of EU ETS and RES-E deployment on $CO_2$ emissions in the Western and Southern European electricity sector and the impact of RES-E deployment on the EUA price. Without a $CO_2$ emission cap and without RES-E injections due to support schemes, aggregated $CO_2$ emissions of the electricity sector would have been considerably higher. The amount of $CO_2$ which was not emitted by the electricity sector can be allocated to EU ETS on the one hand and RES-E deployment on the other hand. Besides, the introduction of RES-E deployment decreased the EUA price.

A remarkable phenomenon is the *$CO_2$ emission interaction* effect between EU ETS and RES-E deployment. By $CO_2$ emission interaction, it is meant in this thesis that the impact of one policy instrument on $CO_2$ emissions in the electricity sector varies according to the presence of the other instrument. As a second aim, this master thesis quantifies the emission interaction between EU ETS and RES-E deployment.

The results presented in this master thesis come from a scenario analysis performed with a model that simulates electricity generation in Europe. The model was specifically built with the goal to achieve the thesis objectives. The focus of the study lies on electricity generation in Western and Southern Europe.

A review of the existing literature shows that a lot of work has been done on the topic of electricity generation under EU ETS and with RES-E deployment. This thesis differs from the existing literature - and therefore offers an added value - in three aspects. First, this thesis focuses on both EU ETS and RES-E deployment, unlike a lot of literature in which the effect of only one policy instrument is examined and the other instrument is considered as a fixed boundary condition. Second, the analysis is performed from a historical point of view. As EU ETS and RES-E deployment are recent phenomena, literature on the topic is mainly aiming to outline prospective scenarios. At the time of writing, no historical analysis was available. Finally, the conclusions presented in this thesis result from a quantitative analysis based on an extended simulation model of the European electricity market. Research results presented in existing literature often follow from theoretical qualitative descriptions or theoretical quantitative models. Examples of papers applying the first approach are Boots et al. [6] and Sorrell et al. [35] whereas Rathmann [32] and De Jonghe et al. [7] apply the second approach.

## 1.3 Thesis structure

Following on this introduction, chapter 2 explains the methodology applied in this master thesis. First, the analysis plan and the different scenarios of the scenario analysis are described. Subsequently, chapter 2 outlines the geographical scope of the analysis and the evolution of the electricity sector, the EUA price and the fuel prices over time. It is important to properly understand the setting in which the scenario analysis is performed.

Chapter 3 describes the electricity generation simulation model used to perform the scenario analysis. Readers only interested in the research results, can limit their reading of this chapter to the summary section at the end of the chapter.

Chapter 4 and chapter 5 present the research results, i.e. a quantitative description of the impact of EU ETS and RES-E deployment on the $CO_2$ emissions in the electricity sector and on the EUA price. The results presented in chapter 4 are based on the assumption that the EUA price is an exogenous parameter, independent of the presence of RES-E injections. The results presented in chapter 5 are based on the assumption that the electricity sector is subject to its own $CO_2$ emission cap. None of both assumptions corresponds to the actual situation of the electricity sector within EU ETS. However, both assumptions define the range in which the actual impact of RES-E deployment and EU ETS is located.

Chapter 6 examines the $CO_2$ emission interaction effect between RES-E deployment and EU ETS. The existence of the emission interaction effect already becomes clear from the results presented in chapter 4 and chapter 5. These chapters, however, merely point out the interaction effect but do not explain the mechanism behind it. Chapter 6 takes a step back and places the emission interaction effect within other ways EU ETS and RES-E deployment interact. Subsequently, this chapter zooms in on the mechanism behind $CO_2$ emission interaction.

Finally, chapter 7 summarizes the conclusions of this master thesis and gives recommendations for further research.

Each chapter concludes with a summary of the analyses and conclusions described in that chapter.

# Chapter 2

# Methodology and scope

This master thesis aims to quantify the impact of EU ETS and RES-E deployment on $CO_2$ emissions in the electricity sector and on the EUA price, with attention to the interaction effect between both policy instruments regarding $CO_2$ emissions. This chapter deals with the applied methodology and scope of this master thesis.

The first two sections describes the methodology. Section 2.1 describes the analysis plan, consisting of four steps. Section 2.2 explains the analysis tool, i.e. a scenario analysis performed with a simulation model of the electricity sector. The different scenarios are described in this section while the simulation model itself is treated in the next chapter (see chapter 3).

The second part of this chapter outlines the scope of this master thesis. Section 2.3 describes the geographical scope and section 2.4 discusses the evolution of the electricity sector over the considered time range. Finally, historical evolution of the EUA price and the fuel prices are outlined in section 2.5. Knowledge of the boundary conditions of the analysis is indispensable in order to properly assess the results presented in this thesis.

## 2.1 Analysis plan

EU ETS caps the aggregated $CO_2$ emissions of all ETS sector and puts a price on the emission of $CO_2$, i.e. the EUA price. RES-E deployment displaces $CO_2$ emissions from the electricity sector to other ETS sectors and reduces the EUA price. This master thesis studies the impact on $CO_2$ emissions in the electricity sector separately from the impact on the EUA price. The impact on $CO_2$ emissions is examined starting from the *ETS-price assumption* and the impact on the EUA price is examined starting from the *ETS-cap assumption.* Both assumptions together define the range in which the actual impact of RES-E deployment and EU ETS on both $CO_2$ emissions in the electricity sector and the EUA price is located.

According to the ETS-price assumption, EU ETS is modeled as an exogenous and invariable EUA price imposed on electricity generators. This implies that RES-E deployment only causes $CO_2$ displacement from the electricity sector to other ETS sectors and that EU ETS causes $CO_2$ abatement in the electricity sector. The effect of EU ETS and RES-E deployment is thus fully expressed in terms of impact on $CO_2$ emissions in the electricity sector. Note that this assumption corresponds to a theoretical situation in which the electricity sector is only responsible for a tiny part of all $CO_2$ emissions covered by EU ETS, meaning that a change in $CO_2$ emissions in the electricity sector has no influence on the EUA price.

According to the ETS-cap assumption, EU ETS is modeled as an exogenous $CO_2$ emission cap imposed on the electricity sector. Within this emission cap, the trade mechanism determines the EUA price. RES-E deployment decreases this EUA price but does not cause $CO_2$ displacement from the electricity sector to other ETS sectors. The impact of EU ETS and RES-E deployment is thus fully expressed in terms of impact on the EUA price. Note that this assumption corresponds to a theoretical situation in which the electricity sector is responsible for all $CO_2$ emissions covered by EU ETS.

Both assumptions corresponds to a theoretical extreme position of the electricity sector within EU ETS. Table 2.1 gives an overview of the actual position and these extreme positions. Note that the actual position of the electricity sector within EU ETS lies between the two extrema.

| | emission share | EUA price | $CO_2$ emissions |
|---|---|---|---|
| actual position | 60 % | variable | variable |
| ETS-price assumption | 0 % | fixed | variable |
| ETS-cap assumption | 100 % | variable | fixed |

TABLE 2.1: Overview of the actual position and theoretical extreme positions of the electricity sector within EU ETS. *Emission share* refers to the share of $CO_2$ emissions coming from the electricity sector in all emissions covered by EU ETS. *EUA price* and *$CO_2$ emissions* refers to the impact of RES-E deployment on respectively the EUA price and $CO_2$ emissions in the electricity sector in presence of EU ETS.

In summary, the analysis plan consist of the following four steps:

1. The impact of EU ETS and RES-E deployment on $CO_2$ emission in the electricity sector is determined, starting from the ETS-price assumption. This $CO_2$ emission impact is overestimated as the EUA price impact is neglected. Results following from this analysis are presented in chapter 4.

2. The impact of EU ETS and RES-E deployment on the EUA price is determined, starting from the ETS-cap assumption. This EUA price impact is overestimated as the $CO_2$ emission impact is neglected. Results following from this analysis are presented in chapter 5.

3. The $CO_2$ emission impact and the EUA price impact are combined to define the range in which the actual impact of EU ETS and RES-E deployment is located. This analysis is presented in chapter 5 as well.
4. The interaction effect between EU ETS and RES-E deployment regarding $CO_2$ emission in the electricity sector is further examined. This part of the analysis stands somewhat apart from the previous analysis steps. This analysis is discussed in chapter 6.

## 2.2 Analysis tool

The analysis tool is a scenario analysis performed with a simulation model of the electricity market. Four different scenarios are considered in the scenario analysis:

- **OBS scenario**. The observed scenario represents the actual market outcome as observed in the period from 2007 to 2010. The simulation model is calibrated to match simulation results in the OBS scenario with historical market data. In the OBS scenario, both EU ETS and RES-E deployment are in place. The EUA price increases marginal generating cost of the power plants and RES-E generation is subtracted from the original electricity demand.
- **RES scenario**. In the RES scenario, only RES-E deployment is present. RES-E generation is subtracted from electricity demand and no EUA price or $CO_2$ emission cap is imposed on the electricity generators.
- **ETS scenario**. In the ETS scenario, only EU ETS is in place and RES-E generation due to RES-E support schemes is set to zero.
- **NOPOL scenario**. In the no-policy scenario, neither EU ETS nor RES-E deployment is in place. No EUA price or $CO_2$ emission cap is imposed on the electricity generators and RES-E generation due to RES-E support schemes is set to zero.

The impact of EU ETS and RES-E deployment on $CO_2$ emissions in the electricity sector is determined as the difference in $CO_2$ emissions between the NOPOL scenario and the OBS scenario, starting from the ETS-price assumption. Based on the RES scenario and the ETS scenario, the total amount of $CO_2$ not emitted by the electricity sector can be allocated to RES-E deployment and EU ETS. The interaction effect between both policy instruments can be assessed by comparing the impact of EU ETS in absence of RES-E deployment (NOPOL scenario versus ETS scenario) and EU ETS in presence of RES-E deployment (RES scenario versus OBS scenario). Analogously, RES-E deployment can be introduced in absence of EU ETS (NOPOL scenario versus RES scenario) or in presence of EU ETS (ETS scenario versus OBS scenario).

The impact of EU ETS and RES-E deployment on the EUA price is determined as the difference in EUA price between the ETS scenario and the OBS scenario, starting from the ETS-cap assumption.

The difference between the ETS-cap assumption and the ETS-price assumption is only reflected in the ETS scenario. The OBS scenario reproduces historical data, regardless whether EU ETS is perceived as an EUA price or as a $CO_2$ emission cap. In the RES scenario and NOPOL scenario, no EU ETS is in place and hence the assumption on EU ETS does not change the simulation results.

Electricity from wind energy, photovoltaic energy and bio-energy (biogas and biomass) is considered as RES-E generation due to RES-E support schemes. These forms of renewable electricity are supported by all European Member States [11]. RES-E generation from other renewable sources is considered as independent from RES-E support schemes. Renewable hydro technologies[1] are mature enough to be economically viable without financial support. Geothermal energy, wave energy and tidal energy are nowadays still marginal in European electricity generation. *RES-E deployment* and *RES-E injections* thus refers in this master thesis to deployment and injections from wind energy, photovoltaic energy and bio-energy.

The model used to perform the scenario analysis considers only operational aspects (see chapter 3). This implies the assumption that the conventional power plant portfolio[2] would have been the same in absence of EU ETS and/or RES-E deployment.

## 2.3 Geographical scope

13 Western and Southern European countries are incorporated in the analysis; Ireland, the United Kingdom, Portugal, Spain, France, Belgium, the Netherlands, Luxembourg, Germany, Denmark, Switzerland, Italy and Austria. Most countries are incorporated because they are part of EU ETS and have at the same time significant RES-E injections due to RES-E support schemes. Luxembourg has very little RES-E generation but is nevertheless included in the model in order to build a complete model of the Western and Southern European electricity market.

Switzerland requires special attention. It is not part of EU ETS and does not join in the renewable energy target of the European Union. Therefore, Switzerland is not included in the scenario analysis but considered as a *dummy country*, meaning that in every scenario electricity in Switzerland is generated in absence of EU ETS but with RES-E injections. $CO_2$ emissions from Swiss electricity generators are not included in the results presented further in this master thesis. Nevertheless, it is important to include Switzerland in the analysis in order to build a complete model of the Western and Southern European electricity market.

[1]Run-of-river plants and hydro dams are meant by *renewable hydro technologies*

[2]With *conventional power plant portfolio* are all power plants meant excluding wind power plants, photovoltaic power plants and biomass and -gas fired plants

| [TWh] | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|
| Austria | 3,3 | 4,4 | 4,4 | 4,4 |
| Belgium | 2,8 | 3,7 | 3,9 | 4,2 |
| Denmark | 9,1 | 8,9 | 10,4 | 11,8 |
| France | 8,6 | 9,8 | 12,2 | 14,3 |
| Germany | 64,5 | 69,9 | 74,0 | 77,6 |
| Ireland | 1,7 | 1,9 | 2,0 | 2,0 |
| Italy | 10,6 | 11,9 | 18,4 | 20,1 |
| Luxembourg | 0,2 | 0,2 | 0,2 | 0,2 |
| Netherlands | 5,8 | 6,9 | 7,7 | 8,2 |
| Portugal | 5,3 | 6,9 | 8,4 | 10,0 |
| Spain | 30,3 | 36,2 | 42,5 | 52,0 |
| United Kingdom | 13,3 | 15,0 | 18,4 | 21,7 |
| Sum MS12 | 155,5 | 175,6 | 202,4 | 226,4 |
| EU-27 | 165,6 | 193,6 | 224,3 | 249,2 |
| Switzerland | 1,7 | 1,3 | 1,4 | 1,5 |

TABLE 2.2: Overview of RES-E generation due to support schemes in every country included in the analysis [19].

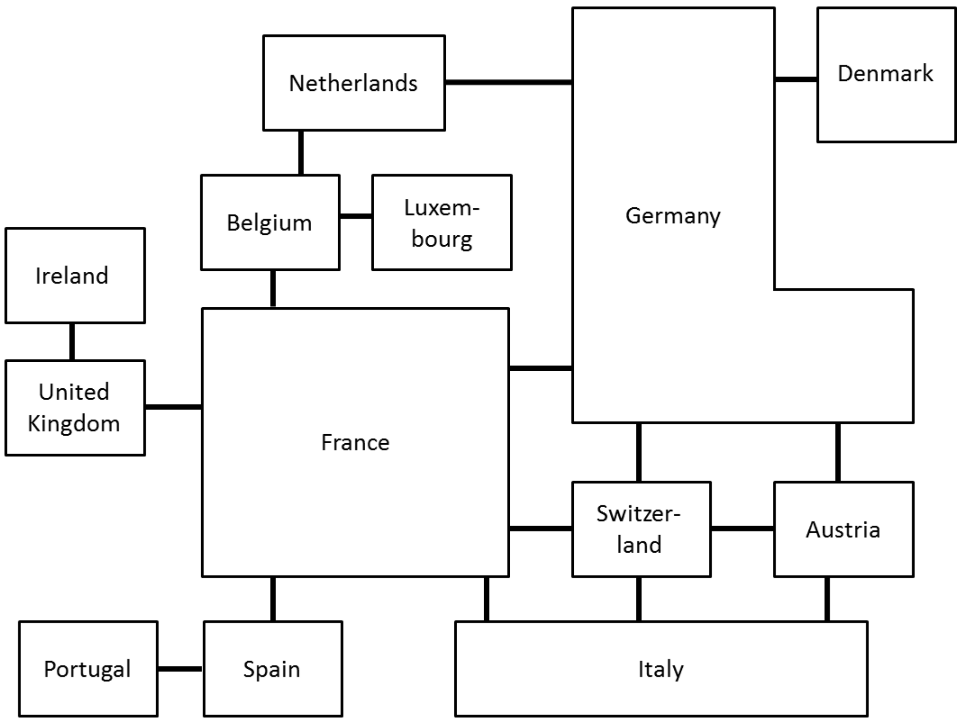



FIGURE 2.1: Schematic overview of the geographical area covered by the model, including cross border transmission lines anno 2010.

Table 2.2 gives an overview of RES-E generation due to RES-E support schemes in every country included in the analysis. It shows that on average 91 % of the RES-E generation in EU-27 from 2007 to 2010 originated from Member States represented in the analysis. For the sake of completeness, RES-E generation in Switzerland is also given.

The 12 European Union Member States included in the analysis will be referred to as *MS12*. Figure 2.1 depicts the geographical scope of the analysis including the cross border transmission lines for 2010.

Of all ETS sectors, only the electricity sector in MS12 is modeled. Further in this thesis, *electricity sector* refers to the electricity sector in MS12 and *other ETS sectors* refers to all non-modeled ETS sectors, i.e. the electricity sectors in EU MS not included in the model and non-electricity sectors in all countries covered by EU ETS.

## 2.4 Evolution of the electricity sector over time

The analysis covers the period from January 1 2007 till December 31 2010. During this time range, the electricity sector was subject to changes in electricity demand, non-supported generation capacity and generation from renewables due to support schemes.

### 2.4.1 Electricity demand

Figure 2.2 shows the evolution of demand for electricity in MS12 from 2007 to 2010. As of the second quarter of 2008, European economy was in recession to emerge from recession in the third quarter of 2009 [?]. This is however hardly translated into a decrease in electricity demand. Aggregated annual electricity demand in MS12 grew from 2.406 TWh in 2007 to 2.482 TWh in 2010. This equates to an average demand growth of 0,8 % per year. Five countries represent 85 % of total electricity demand, i.e. Germany, France, the United Kingdom, Italy and Spain.

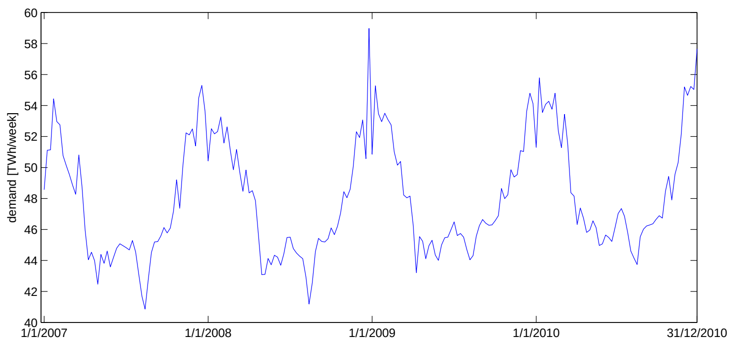



FIGURE 2.2: Evolution of weekly electricity demand in MS12 from 1/1/2007 to 31/1/2010 [18][19].

### 2.4.2 Non-supported generation capacity

Table 2.3 presents the evolution of installed non-supported generation capacity from 2007 to 2010 in all countries included in the analysis (MS12 and Switzerland). This table includes nuclear power plants, coal fired and lignite fired power plants, combined cycle power plants, peak power plants (gas turbines and internal combustion units) and other capacity of minor importance (run-of-river plants, geothermal power plants and waste based power plants). The largest change in the conventional power plant portfolio is the increase of combined cycle power plants. 18 GW of combined cycle capacity is commissioned during the considered period. There is a little decrease in installed diesel generators of 4 GW from 2007 to 2010. Installed capacity of the other power plants barely changes.

The data presented in table 2.3 includes cogeneration plants. The installed cogeneration capacity increased from 85 GW in 2007 to 89 GW in 2010.

| [GW] | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|
| Nuclear | 112 | 112 | 112 | 111 |
| Coal and lignite | 123 | 123 | 122 | 122 |
| Combined cycle | 144 | 151 | 156 | 162 |
| Peak units | 79 | 78 | 77 | 75 |
| Others | 34 | 35 | 36 | 36 |

TABLE 2.3: Evolution of installed non-supported generation capacity from 2007 to 2010, including cogeneration. Aggregated data for all countries in the analysis (MS12 and Switzerland). *Peak units* are gas turbines and internal combustion units and *others* refers to run-of-river plants, geothermal power plants and waste based power plants.

### 2.4.3 RES-E generation

Only RES-E capacity due to support schemes is dealt with in this paragraph. Electricity generation from renewable energy sources due to support schemes increased significantly over the period 2007 - 2010, as shown in table 2.4. RES-E generation increased from 156 TWh or 6,5 % of total generation in 2007 to 226 TWh or 9,1 % of total generation in 2010. RES-E generation in 2008 was 176 TWh or 7,3 % of total generation and 202 TWh or 8,3 % of total generation in 2009.

Wind energy is the most important supported renewable electricity source, generating on average 62 % of supported renewable electricity. Biomass and biogas power plants, including cogeneration, generate on average 32 % of supported renewable electricity and solar energy contributes on average only 6 %. However, solar energy is the renewable energy source with the largest relative growth in generation, increasing with more than a factor five in four years. Wind energy shows the largest absolute growth, increasing produced energy with 36,7 TWh from 2007 to 2010.

| [TWh] | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|
| Sun | 3,8 | 7,4 | 14,2 | 20,4 |
| Biomass and biogas | 52,4 | 56,6 | 64,4 | 70,0 |
| Wind | 99,3 | 111,6 | 123,8 | 136,0 |
| Total | 155,5 | 175,6 | 202,4 | 226,4 |

TABLE 2.4: Overview of RES-E generation from wind energy, solar energy and bio-energy in MS12 [19].

Germany and Spain are by far the largest producers of supported renewable electricity (see table 2.2). Germany is responsible for 38 % and Spain for 21 % of supported renewable electricity generated from 2007 to 2010.

## 2.5 Evolution of prices over time

Electricity generation is influenced by the EUA price and fuel prices. The period from 2007 to 2010 can be divided in three subperiods based on these prices.

### 2.5.1 EUA price

Figure 2.3 show the historical EUA price. The considered time range can be divided in three subranges:

- January 2007 - December 2007: very low EUA price because banking of allowances from the first EU ETS phase to the second EU ETS phase was not allowed.
- January 2008 - April 2009: upsurge in EUA price up to 28,72 EUR/t$CO_2$ followed by a downfall to 8,24 EUR/t$CO_2$ due to economic recession.
- May 2009 - December 2010: stable EUA price on an average of 14,15 EUR/t$CO_2$.

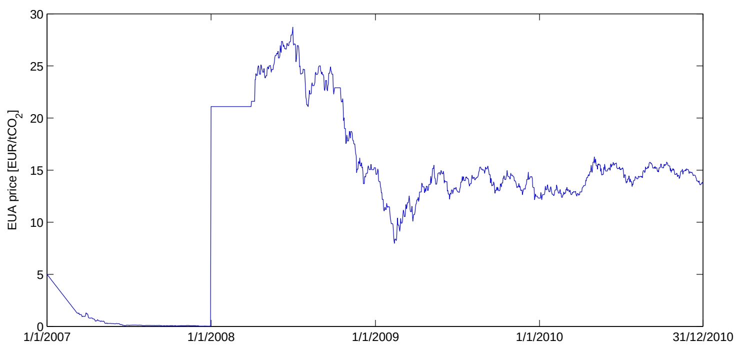



FIGURE 2.3: Historical EUA price from 1/1/2007 to 31/1/2010 [5].

### 2.5.2 Fuel prices

Besides the EUA price, also fuel prices determine the impact of EU ETS. Figure 2.4, figure 2.5 and figure 2.6 give daily market prices for respectively coal, natural gas and oil. The considered time range can be divided in the same subranges as the ones used for the EUA price. In 2007, fuel prices were increasing steadily starting from relatively low price levels. For all fuels, prices peaked in the summer of 2008 after which they collapsed to less than half the peak price. As of mid-2009, prices start increasing steadily again. Figure 2.7 shows the gas/coal price ratio for 2007 till 2010. The price ratio is based on the average coal price and average natural gas price.

As explained by Delarue [10], EU ETS causes $CO_2$ abatement on the short term[3] by means of fuel switching. Fuel switching is the result of moving coal fired power plants up in the merit order, from active use to reserve, and gas fired power plants down, from reserve to active use. More fuel switching occurs when the EUA price is high and difference in gas price and coal price is low. The EUA price and the fuel prices give however only a first indication of the fuel switching effect. Fuel switching also depends on electricity demand, power plant portfolio and RES-E generation.

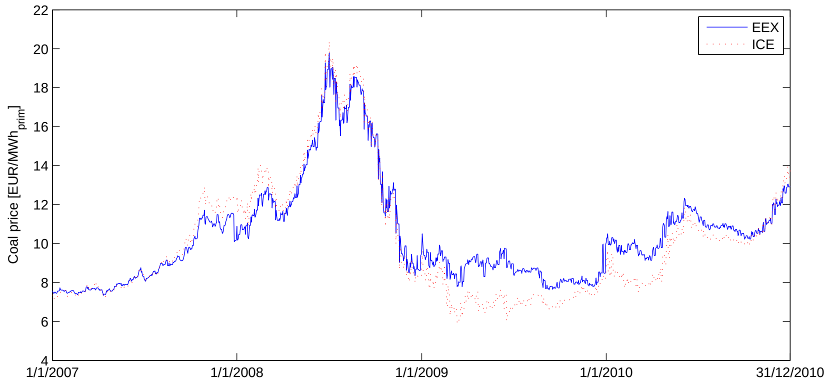



FIGURE 2.4: Historical coal prices from 1/1/2007 to 31/1/2010 [12][25].

[3] *Short term* means that only operational aspects of the power plant portfolio are considered.

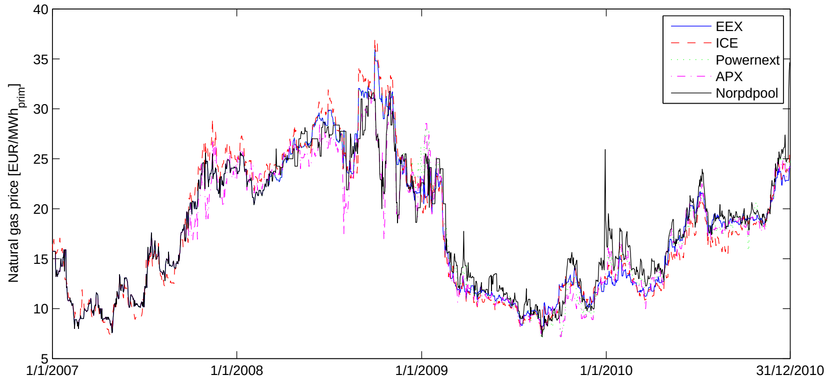



FIGURE 2.5: Historical natural gas prices from 1/1/2007 to 31/1/2010 [12][25][31][3][29].

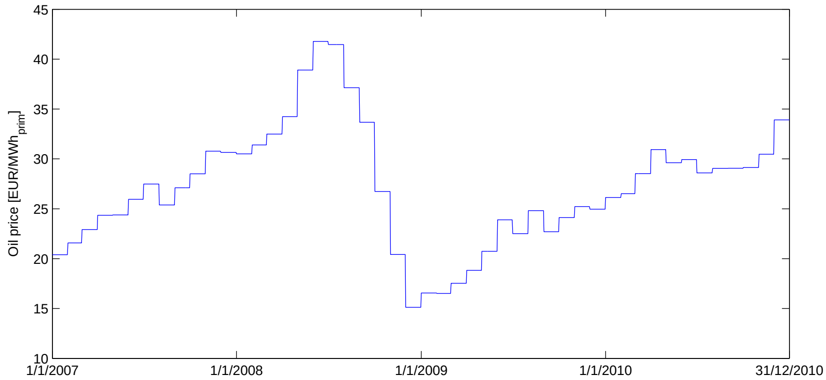



FIGURE 2.6: Historical oil price from 1/1/2007 to 31/1/2010 [26].

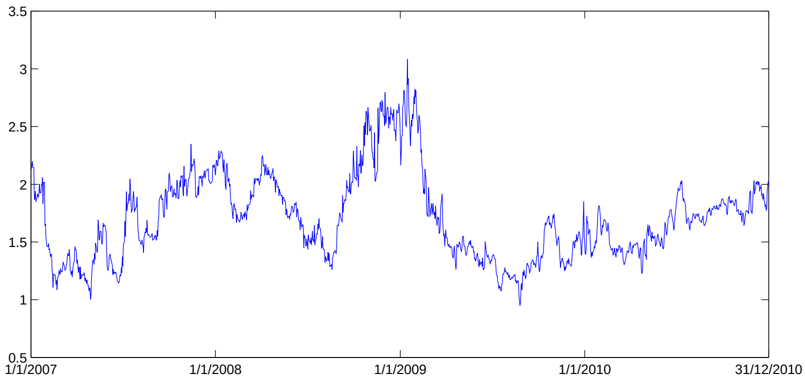



FIGURE 2.7: Ratio of natural gas price and coal gas price from 1/1/2007 to 31/1/2010.

## 2.6 Summary

This master thesis quantifies the impact of EU ETS and RES-E deployment on $CO_2$ emissions in the electricity sector and on the EUA price. EU ETS caps the aggregated $CO_2$ emissions of all ETS sectors and puts a price on the emission of $CO_2$. RES-E deployment displaces $CO_2$ emission from the electricity sector to other ETS sectors and reduces the EUA price. The impact of EU ETS and RES-E deployment on $CO_2$ emissions in the electricity sector is determined starting from the ETS-price assumption. According to this assumption, the electricity sector is subject to an exogenous and invariable EUA price imposed by EU ETS. The impact of EU ETS and RES-E deployment on the EUA price is determined starting from the ETS-cap assumption. According to this assumption, the electricity sector is subject to a $CO_2$ emission cap imposed by EU ETS. The combination of both assumptions define the range in which the actual impact of RES-E deployment and EU ETS on both $CO_2$ emissions in the electricity sector and the EUA price is located.

The research question of this thesis is answered by means of a scenario analysis conducted with a simulation model of the electricity market. Four scenarios are examined, i.e. electricity generation under EU ETS and RES-E deployment (OBS scenario), electricity generation with only EU ETS in place (ETS scenario), electricity generation with only RES-E deployment in place (RES scenario) and electricity generation without one of both in place (NOPOL scenario). The impact of EU ETS and RES-E deployment can be determined as the difference in $CO_2$ emissions and EUA price between the different scenarios.

The analysis covers the electricity sector in twelve European Member States in Western and Southern Europe, referred to as MS12. Switzerland is added to the model in order to build a complete network of the Western and Southern European electricity market.

The analysis covers the years 2007, 2008, 2009 and 2010. During this period, aggregated electricity demand increased by 0,8 % per year on average and installed conventional generation capacity hardly changed. RES-E generation due to RES-E support schemes increased from 156 TWh or 6,5 % of total generation in 2007 to 226 TWh or 9,1 % of total generation in 2010. RES-E generation in 2008 was 176 TWh or 7,3 % of total generation and 202 TWh or 8,3 % of total generation in 2009. Wind energy, solar energy and bio-energy are considered as renewable electricity sources stimulated by RES-E support schemes.

The period 2007-2010 can be divided in three subperiods based on the EUA price and fuel prices. The first subperiod covers 2007 and is characterized by a very low EUA price and steadily increasing fuel prices. The second subperiod starts as of the beginning of 2008, when the EUA price and fuel prices show a strong upsurge to peak mid-2008. Subsequently, the EUA price and fuel prices fall dramatically due to economic recession to stabilize in the first half of 2009. The third subperiod runs from mid-2009 to the end of 2010 and is characterized by a stable EUA price on an average price level of 14,15 EUR/t$CO_2$ and slowly increasing fuel prices.

# Chapter 3

# Electricity generation simulation model

The scenario analysis is performed with an electricity generation simulation model. This model allows to simulate electricity generation in 13 interconnected European countries from 2007 to 2010. Two settings are possible with regard to RES-E deployment - with or without RES-E deployment - and three with regard to EU ETS - EUA price, $CO_2$ emission cap or none of both.

The model returns hourly generation of each power plant type in each country, hourly $CO_2$ emissions of each power plant type in each country, hourly electricity price in each country and hourly cross border transmission.

## 3.1 Characteristics of the model

The characteristics of the model are discussed according to the classification parameters proposed by Delarue [9].

The model is based on the principle of perfect competition between power generators. This means that the electricity supply curve equals the marginal generation cost curve. The demand for electricity is considered inelastic. This is a fair simplification as only short term aspects are taken into account. The model has one objective function, i.e. to minimize total generation and transmission cost. The electrical network is modeled as a trade based network in which neighboring countries are connected through interconnections with limited capacity. Table 3.1 gives an overview of the classification parameters of the model.

The model covers a time range of four years, from 2007 to 2010. This period is divided in time steps of one hour. Relative time-independent data like installed capacity and net transfer capacity are given for each of the four years. To limit the model's calculation time, optimization of electricity generation happens in blocks of one week.
The geographical area covered by the model consists of 13 countries in Western

| | |
|---|---|
| Degree of competition | Perfect competition |
| Objective function | Single objective |
| Demand curve | No demand elasticity |
| Time frame | Short term - operational aspects |
| Electrical network | Trade based interconnections |
| Use of the model | Simulating events |

Table 3.1: Classification parameters of the model

and Southern Europe: Austria, Belgium, Denmark, France, Germany, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Switzerland and the United Kingdom. The technical dimension incorporates 23 different types of power plants. All the power plants of the same type are grouped per country and considered as one power plant with a set of characteristics and a power output ranging from zero to the total installed capacity. In a scenario analysis without RES-E deployment, wind power plants, photovoltaic power plants and biomass and -gas plants are excluded of the model. Table 3.2 presents an overview of the different types of power plants represented in the model. Steam thermal units on natural gas and oil are, because of their limited installed capacity, not considered as a separate power plant type but added to steam thermal units on coal.

The model runs through different steps while simulating. Figure 3.1 shows an overview of the model's algorithm. The required input consists of data for each country (e.g. installed capacity of different types of power plants), overall data (e.g. interconnection capacities) and the preferred scenario (e.g. with or without RES-E deployment). Before electricity generation is calculated by minimizing the total generation cost, the original demand is corrected to take account of RES-E production and single storage. In a final step, the result of the cost minimization is processed to the desired output format.

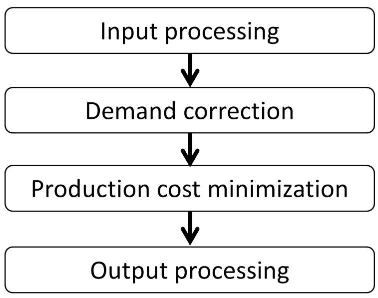



Figure 3.1: Overview of the model's algorithm

Nuclear power plant
Steam thermal units on coal with 3 possible rated efficiencies
Steam thermal units on lignite
Combined cycle units on natural gas with 3 possible rated efficiencies
Gas turbine units on natural gas
Internal combustion units on oil
Wind power plants
Photovoltaic power plants
Hydro power: run-of-river plants
Steam thermal units on waste
Steam thermal units on biomass and biogas
Geothermal power plants
Cogeneration steam thermal units on biomass or biogas
Cogeneration steam thermal units on coal
Cogeneration internal combustion units on oil
Cogeneration gas turbine units on natural gas
Cogeneration combined cycle units on natural gas
Single storage plants
Dual storage plants

Table 3.2: Overview of power plant types used in the model

## 3.2 Input data

Three different types of input data are required. First, the desired scenario needs to be entered by the user. A scenario consists of a year (2007, 2008, 2009 or 2010), a setting for EU ETS (EUA price, $CO_2$ emission cap or none of both) and a setting for RES-E support (with or without RES-E deployment). Subsequently, the following data are needed per country:

- installed capacity for each power plant type in MW
- hourly electricity demand in MWh/h
- hourly produced wind energy in MWh/h
- hourly cogeneration profile
- hourly solar profile
- daily fuel prices in EUR/MWh$_{prim}$

Finally, the following overall data are needed:

- technical characteristics of the power plants

- daily EUA price in EUR/t$CO_2$
- net transfer capacity (NTC) between countries in MW

The electricity generation system used in the model is based on data presented in the Power Statistics Report from EURELECTRIC, edition 2010 [19]. The power plant characteristics are averages of the power plants represented in the simulation model E-simulate [40]. As mentioned before, all power plants in a country of the same type are considered as one power plant with one set of characteristics, i.e. fuel, rated efficiency and $CO_2$ emission rate. The power plant characteristics are assumed to be the same in all countries. The rated efficiency of a cogeneration plant is the efficiency of the best available technology to generate electricity with the same fuel. This is important in order to properly allocate fuel cost and $CO_2$ emissions to the electric output of the cogeneration plant.

Hourly electricity demand data originates from ENTSO-E [18] for the countries on the European mainland, from EirGrid [13] for Ireland and from the National Grid Company [27] for the United Kingdom. These original demand data are adapted to take into account neglected international transmission lines between countries included in the model and countries excluded of the model. The demand of a net importer is decreased and the demand of a net exporter is increased with the neglected transported energy. This demand correction is done on a monthly basis.

The hourly wind energy production is taken from national TSO's EirGrid [13], REN [34], REE [33], Terna [37], Amprion [2], EnBW Transportnetze AG [16], 50 Hz [1], Tennet [36], Energinet [17] and Elia [14]. The wind production of Luxembourg, Switzerland, the United Kingdom, France, Austria and the Netherlands is obtained as the capacity weighted average of the wind production in the neighboring countries.

The cogeneration profile is based on the one used in E-simulate [40]. It is a combination of a flat profile, typical of the industrial sector, and a more fluctuating profile, typical of the gardening sector. The ratio in which both profiles are combined differs from country to country. The multiplication of the installed cogeneration capacity and the cogeneration profile gives the hourly electricity generation from cogeneration plants.

The solar profile is based on data from the Photovoltaic Geographical Information System [30]. By using solar irradiation data, the assumption is made that the power output of a photovoltaic panel scales linearly with solar irradiation, without an upper or lower limit. The solar profile is the same for the United Kingdom and Ireland, Switzerland and Austria, Portugal and Spain and the Benelux countries. Hence, 8 different solar profiles are used in the model.

Fuel prices are available at open databases from different commodity exchanges and the protected database from Thomson Reuters [38]. The TTF gas price from APX-ENDEX [3] is used in the Benelux, the Nord Pool Gas price from Nord Pool [29] is used in Denmark, the PEG Nord gas price from Powernext [31] is used in

France, Spain, Portugal and Italy, the European gas index from EEX [12] is used in Germany, Austria and Switzerland and the ICE natural gas price [25] is used in the United Kingdom and Ireland. All natural gas prices are day ahead prices. For coal, only two different prices are considered. The API 2 coal price from EEX [12] is used on the European mainland and the Rotterdam coal price from ICE [25] is used in the United Kingdom and Ireland. The coal prices are quarterly future. The Brent monthly future, available on Index Mundi [26], is used as oil price in all countries. The price for lignite, uranium, biomass and biogas is considered as constant as these fuels are not traded on international exchanges.

Finally, the EUA price and transmission capacity between the different countries are needed. The EUA price originates from BlueNext [5] and the NTC data for the summer from ENTSO-E [18] are taken as international transmission capacity. By applying NTC data for the summer in the winter, international transport is restrained in the winter as the actual NTC is larger in the winter due to colder weather. Luxembourg is modeled as a part of Belgium by setting the transmission capacity between both countries infinite.

Electricity demand data, wind generation data, cogeneration data and solar data are scaled to EURELECTRIC data in order to align the different data sources. Peak demand data and the sum of hourly demand data from ENTSO-E are scaled to the peak demand and aggregated demand from EURELECTRIC. Wind data, cogeneration profile and solar profile are scaled so that the sum of the hourly produced electricity matches the aggregated EURELECTRIC data. Missing data are determined by linear interpolation. All the hourly data for Ireland and the United Kingdom are shifted one hour to compensate the time difference.

## 3.3 Description of the model

The model is formulated as a linear program in the General Algebraic Modeling System (GAMS) and solved using the CPLEX solver. The input and output of the linear optimization problem is processed in Matlab. As the optimization is not solvable in one model run, each year is divided and solved in weekly blocks.

The model determines optimal electricity generation as the solution with lowest aggregated generation cost. A small cost is allocated to international transmission. Hence, the objective function is

$$min\left(\sum_{i,j,t} MC_{i,j,t} * gen_{i,j,t} + \sum_{j,j_2,t} |cbt_{j,j_2,t}| * TC\right) \tag{3.1}$$

with $i$ the type of power plant, $j$ the country and $t$ the time. $MC_{i,j,t}$ is the marginal generation cost of a power plant type in EUR/MWh, $gen_{i,j,t}$ the generated electricity in MWh/h, $cbt_{j,j_2,t}$ the cross border transmission in MWh/h from country $j_2$ to country $j$ and $TC$ the cross border transmission cost in EUR/MWh. $TC$ equals 0,25 EUR/MWh which corresponds to a transmission cost of 0,50 EUR/MWh as $cbt_{j,j_2,t}$

is an antisymmetric matrix containing both transmission from $j_2$ to $j$ and from $j$ to $j_2$. The transmission cost is set fixed to this level in order to roughly match the total international transmission in the OBS scenario with historical electricity exchange data.

The marginal generation cost follows from

$$MC_{i,j,t} = \frac{FP_{t,j}}{\eta_i} + \frac{EF_i * EUA\_price_t}{\eta_i} \tag{3.2}$$

with $FP_{t,j}$ the fuel price in EUR/MWh$_{prim}$, $EF_i$ the emission factor of the power plant type in tCO$_2$/MWh$_{prim}$, $\eta_i$ the rated efficiency of the power plant type and $EUA\_price_t$ the EUA price in EUR/tCO$_2$.

The solution of the objective function has to satisfy the following constraints:

Demand constraint:

$$\forall j, t \quad \sum_i gen_{i,j,t} + \sum_{j_2} cbt_{j,j_2,t} = demand_{t,j} \tag{3.3}$$

Power constraint:

$$\forall i, j, t \quad 0 \leq gen_{i,j,t} \leq cap_{i,j} * AF_{i,j} \tag{3.4}$$

Cross border transmission constraints:

$$\forall j, j_2, t \quad |cbt_{j,j_2,t}| \leq NTC_{j,j_2} \tag{3.5}$$

$$\forall j, j_2, t \quad cbt_{j,j_2,t} = -cbt_{j_2,j,t} \tag{3.6}$$

Ramping constraints:

$$\forall j, j_2, t \quad gen_{i,j,t} \leq gen_{i,j,t-1} + cap_{i,j} * RF_{i,j} \tag{3.7}$$

$$\forall j, j_2, t \quad gen_{i,j,t} \geq gen_{i,j,t-1} - cap_{i,j} * RF_{i,j} \tag{3.8}$$

with $demand_{t,j}$ the electricity demand in MWh/h, $cap_{i,j}$ the installed capacity of the power plant type in MW, $AF_{i,j}$ the availability factor of the power plant type, $NTC_{j,j_2}$ the net transfer capacity from country $j_2$ to $j$ in MW and $RF_{i,j}$ the ramping factor of the power plant type.

Electricity prices are derived as the dual of the demand constraint. No unit commitment is implemented in the model as all power plants in each country of the same type are considered as one power plant.

A $CO_2$ emission cap constraint is added in a scenario with a $CO_2$ emission cap imposed on the electricity sector. The exogenous EUA price is then set to zero.

$CO_2$ emission cap constraint:

$$\sum_{i,j,t} \frac{gen_{i,j,t} * EF_i}{\eta_i} \leq CO_2\_cap \tag{3.9}$$

with $CO_2\_cap$ the $CO_2$ emission cap in $tCO_2$/year. In this case, the EUA price is derived as the dual of the $CO_2$ emission cap constraint.

In a scenario without EU ETS, the exogenous EUA price is set to zero and the $CO_2$ emission cap constraint is not considered. In a scenario without RES-E deployment, renewable capacity due to support schemes is set to zero.

## 3.4 Renewables and cogeneration

The modeling of renewable power generation and power generation from cogeneration requires a specific approach. Unlike conventional power plants, the power output of renewable power plants and cogeneration plants is often not driven by electricity demand but by other factors such as meteorological conditions or heat demand. The following renewable energy sources are dealt with; wind energy, solar energy, hydro energy and geothermal energy.

Wind power, photovoltaic power, geothermal power and power from cogeneration are implemented as negative loads. This means that generation from these power sources is subtracted from the electricity demand. Consequently, the demand constraint (see equation 3.3) changes to

$$\forall j,t \quad \sum_{i} gen_{i,j,t} + \sum_{j_2} cbt_{j,j_2,t} = demand\_cor_{t,j} \tag{3.10}$$

with

$$demand\_cor_{t,j} = demand_{t,j} - P_{wind,t,j} - P_{PV,t,j} - P_{geo,t,j} - P_{cog,t,j} \tag{3.11}$$

and $P_{wind,t,j}$, $P_{PV,t,j}$, $P_{geo,t,j}$ and $P_{cog,t,j}$ the power output of respectively wind power plants, photovoltaic power plants, geothermal power plants and cogeneration plants in MWh/h.

Wind energy and photovoltaic energy are intermittent power sources, meaning that their power output is variable - they have a non-dispatchable character - and unpredictable. The modeling of these energy sources is based on historical generation data. As such, wind power and photovoltaic power are implemented as predictable but still non-dispatchable.

### 3.4.1 Wind power

The power output of a wind turbine mainly depends on the wind speed. Since the wind speed varies strongly in time, power output varies as well. The fluctuations in wind power are unpredictable as the wind speed does not follow a specific pattern.

In the model, historical wind production data are used in order to model wind power properly. The wind data are scaled in order to match aggregated hourly generation with historical annual generation from EURELECTRIC [19]. Wind power is by far the form of renewable energy due to RES-E support schemes with the largest installed capacity. Therefore it is of great importance to model wind energy correctly by using historical data in order to study the effect of RES-E deployment accurately.

Wind power is considered as a negative load, decreasing the electricity demand. The rationale behind this is that the power output of a wind turbine is not electricity demand driven but determined by wind conditions.

### 3.4.2 Photovoltaic power

The power output of a photovoltaic panel depends on the solar irradiation and is therefore fluctuating. Unlike wind speed, solar irradiation follows a more strict pattern. Photovoltaic power output is modeled as the product of installed capacity and a solar profile. The solar profile is scaled in order to match aggregated hourly generation with historical annual generation from EURELECTRIC [19]. The solar profiles for Spain and the Benelux are presented as example in figure 3.2. Despite the strong increase in installed photovoltaic power, photovoltaic electricity stays marginal in total electricity generation. This makes it difficult to calibrate photovoltaic power output properly, resulting in large relative faults on the annual photovoltaic electricity generation. This fault is however negligible compared to the total annual electricity generation.

Photovoltaic power is considered as a negative load as the power output of a photovoltaic panel is determined by solar conditions and not by demand for electricity.

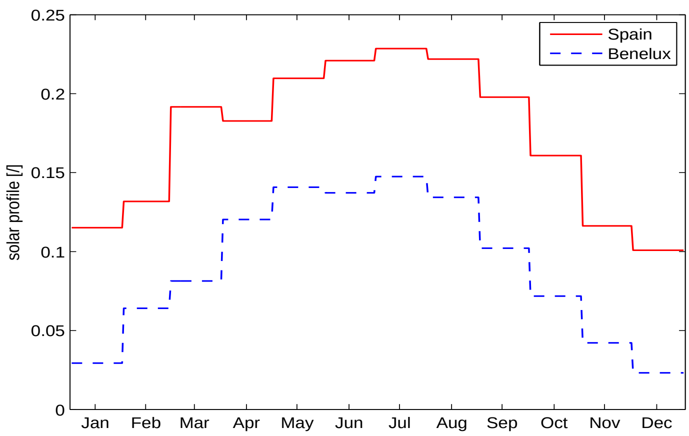



FIGURE 3.2: Solar profile for Spain and the Benelux in 2010 (daily average values).

### 3.4.3 Hydropower

Three different types of hydropower plants can be distinguished; run-of-river plants, pump units and water dams. Pump units and water dams are storage units, further discussed in section 3.5 of this chapter. Run-of-river plants are hydro plants without the possibility to store water. They are modeled as a part of the generation cost minimization.

### 3.4.4 Geothermal power

The amount of electricity produced from geothermal energy in Europe is very limited. Only France, Italy and Portugal have geothermal power plants. In these countries, the share of geothermal energy in total electricity generation is up to maximum 2 %. Geothermal energy is thus a marginal power generating technology in Western and Southern Europe. Geothermal energy is considered as a negative load and assumed to have a constant power output.

### 3.4.5 Cogeneration of heat and power

A cogeneration power plant produces simultaneously heat and electricity. A properly used cogeneration plant is heat demand driven. Cogeneration plants are mainly used in the industrial sector and the gardening sector. These sectors have a typical heat demand profile. For industry, the heat demand profile is relatively flat, while the heat demand profile for the gardening sector is more fluctuating. A profile for the electric output of a cogeneration power plant can be derived from the combined heat demand profile of both sectors. The multiplication of the electric output profile with the installed cogeneration capacity gives the hourly produced electricity. The cogeneration profile is scaled in order to match aggregated hourly generation with historical annual generation from EURELECTRIC [19]. Figure 3.3 shows as example the electric output profile of cogeneration plants in the United Kingdom in 2010.

An important issue with regard to cogeneration plants is the allocation of $CO_2$ emissions and fuel use to the heat and power output. In the model, the allocation to the power output is based on the *best available technique principle.* This implies that the same fuel use and $CO_2$ emissions are allocated to the power output of the cogeneration plant as the fuel use and $CO_2$ emissions of the best available power generating technology with the same power output and based on the same fuel as the cogeneration plant.

Electricity from cogeneration power plants is considered as a negative load. The rationale behind this is that cogeneration is heat demand driven rather than electricity demand driven. In Denmark and the Netherlands, part of the installed cogeneration capacity is considered to be electricity demand driven and included in the cost minimization. In these countries, the installed capacity of cogeneration plants is up to respectively 66 % and 50 % of the total installed capacity. Therefore some of the installed cogeneration capacity has to be dispatchable in order to balance electric supply to demand.

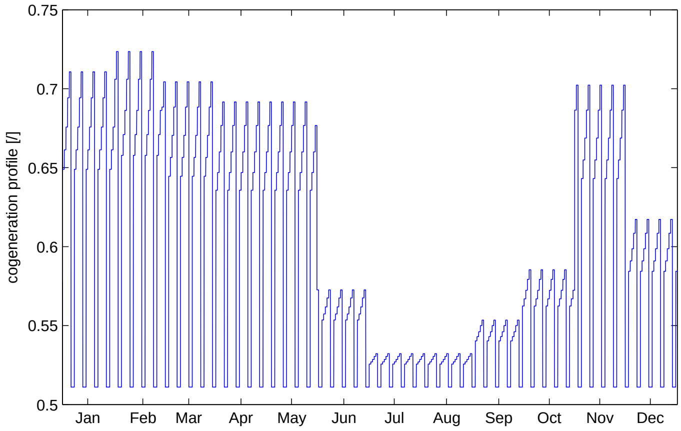



FIGURE 3.3: Electric cogeneration profile for the United Kingdom in 2010 (hourly values).

## 3.5 Storage

Two different types of storage units are considered: single storage units en dual storage units. Single storage units are power plants where energy is stored without electricity consumption. An example of a single storage power plant is a water dam. Dual storage units consume electricity to store energy. An example of a dual storage power plant is a water-pumping unit.

### 3.5.1 Single storage

Single storage plants are mainly used as seasonal storage. Water is stored in periods of high rainfall and used later to generate electricity. Single storage plants tend to smooth out the electricity demand on an annual basis. 8 out of the 13 countries in the model have single storage plants; Ireland, the United Kingdom, Portugal, Spain, France, Luxembourg, Germany and Italy.

Single storage is implemented as a demand correction. The model looks for the day with highest daily electricity demand and reduces this demand, maintaining the shape of the daily demand profile. This process is repeated in an iterative loop until aggregated single storage generation reaches historical single storage generation. The demand adjustment per day is limited by the installed single storage capacity. This results in a corrected demand given by the following equation:

$$demand\_cor_{t,j} = demand_{t,j} - P_{wind,t,j} - P_{solar,t,j} - P_{geo,t,j} - P_{cog,t,j} - P_{ss,t,j} \quad (3.12)$$

with $P_{ss,t,j}$ the power output of the single storage plants in MWh/h. Equation 3.12 replaces equation 3.11 and goes together with the demand constraint (see equation 3.10).

Figure 3.4 shows the effect of single storage on the German demand profile during the week from Monday December 6 2010 till Sunday December 12 2010. Due to high electricity demand in winter, single storage is continuously used. The daily fluctuation in demand is maintained. Note that demand after single storage correction during weekdays is still larger than original demand during weekend days. This indicates that single storage capacity is fully used during weekdays.

Figure 3.5 shows the effect of single storage on an annual basis for Spain. Single storage generation fluctuates clearly in cycles with maximal production in the first half of the year. Similar figures can be drawn for Ireland, the United Kingdom, Portugal, France, Luxembourg, Germany and Italy.

### 3.5.2 Dual storage

Dual storage power plants tend to smooth out the demand profile on a daily basis. Unlike single storage, the basin of a dual storage plant can be emptied and refilled almost daily. Dual storage will be used when the difference in electricity price at the moment of charging and at the moment of releasing is high enough to compensate for the energetic losses during charging and releasing, i.e. when the ratio of the price at charging time and the price at releasing time is smaller than the efficiency of the dual storage plant. The efficiency of dual storage plants in the model is 75 %. Of all countries in the model, only the Netherlands and Denmark have no dual storage plants.

Dual storage is incorporated in the optimization based on the method presented by Wood and Wollenberg [42]. The demand constraint (see equation 3.10) changes and additional constraints are added to the model.

Demand constraint including dual storage:

$$\forall j,t \quad \sum_i gen_{i,j,t} + \sum_{j_2} cbt_{j,j_2,t} = demand\_cor_{t,j} - rel_{t,j} + char_{t,j} \tag{3.13}$$

with $rel_{t,j}$ and $char_{t,j}$ respectively the releasing rate and charging rate of the pump unit in MWh/h.

The energy content of the pump unit is given by ;

$$\forall j,t \quad pump\_energy_{t,j} = pump\_energy_{t-1,j} + char_{t,j} * \sqrt{\eta} - \frac{rel_{t,j}}{\sqrt{\eta}} \tag{3.14}$$

with $pump\_energy_{t,j}$ the energy content in MWh and $\eta$ the rated efficiency of the dual store unit. Releasing efficiency and charging efficiency are assumed to be the same and equal to $\sqrt{\eta}$.

The energy content of the dual storage unit at the end of the simulation must be equal to the initial energy content. Besides, maximum and minimum charging rate, releasing rate and energy content must be respected at all times. This results in four additional constraints.

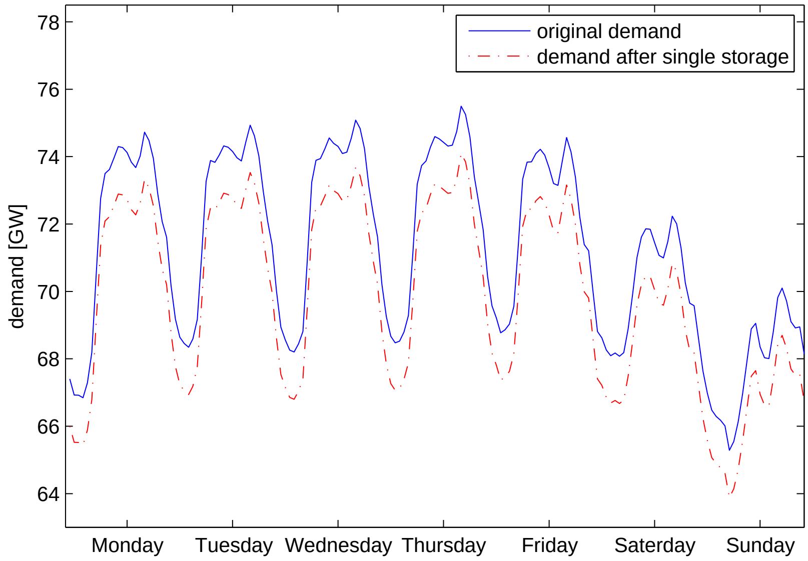



FIGURE 3.4: Effect of single storage on the electricity demand on a daily basis in Germany from Monday 6/12/2010 to Sunday 12/12/2010 (hourly values).

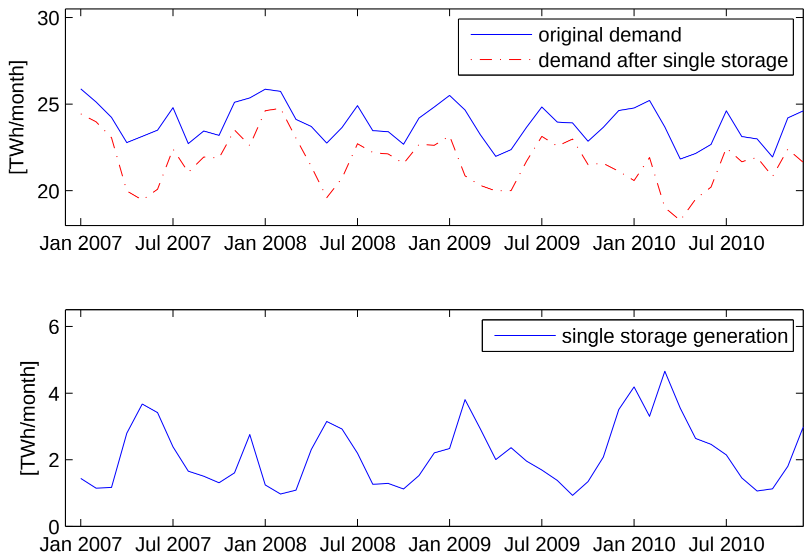



FIGURE 3.5: Effect of single storage on the electricity demand on an annual basis in Spain from January 2007 to December 2010 (monthly aggregated values).

Energy balance constraint:

$$\forall j \quad \sum_t rel_{t,j} = \sum_t char_{t,j} * \eta \tag{3.15}$$

Power and energy content constraints:

$$\forall t, j \quad 0 \leq rel_{t,j} \leq cap\_dual\_storage_j \tag{3.16}$$

$$\forall t, j \quad 0 \leq char_{t,j} \leq \frac{cap\_dual\_storage_j}{\eta} \tag{3.17}$$

$$\forall t, j \quad 0 \leq pump\_energy_{t,j} \leq pump\_energy\_max_j \tag{3.18}$$

with $cap\_dual\_storage_j$ and $pump\_energy\_max_j$ respectively the installed dual storage capacity in MW and the maximum energy content of the dual storage unit in MWh.

Almost no dual storage is used in the model because of the low volatility of electricity prices. Electricity prices are set by the marginal generation cost of the last operating power plant in the merit order. As only a limited number of power plant types are implemented in the model, there is little variation in generation cost of the last generating power plant.

## 3.6 Calibration of the model

The model is based on some simplifications which cause deviation between the OBS scenario and historical observed data. A first important simplification is the assumption that electricity generation and transmission between different countries is perfectly competitive. Another important simplification is that all power plants of the same type are grouped per country and that their characteristics are assumed to be uniform throughout Europe, leading to a limited number of different types of power plants represented in the model. The model also neglects operational contract considerations and uses standard availabilities and ramp rates. Finally, only two coal commodities, one oil commodity and six natural gas commodities are incorporated in the model whereas in reality generators buy more types of commodities. The uncalibrated model shows an overproduction of combined cycle power plants and an underproduction of coal power plants in 2009 and 2010. This contradicts the trend observed by Delarue et al. [10] and Weigt et al. [41]. In 2007 and 2008, the uncalibrated model shows the opposite effect with an overproduction of coal power plants and an underproduction of combined cycle power plants.

A calibration of the model is needed to make the simulation results more realistic. As shown by Delarue et al. [10], a model that is not corrected for the assumptions made, leads to significant errors in estimating residual quantities like emission abatement. The goal of the calibration is to reproduce historical generation data in the OBS scenario of the model. The model is calibrated in five steps.

1. The hourly demand data from ENTSO-E are scaled to match peak demand data and aggregated demand data from EURELECTRIC. This is needed to overcome the deviation between ENTSO-E data and EURELECTRIC data. On average, the aggregated demand from EURELECTRIC is 7 % larger than the sum of hourly demand from ENTSO-E.

2. Generation of power plant types whose power output is independent from RES-E injections or the presence of EU ETS, is set to historical generation levels. This can be done as the generation of these power plant types is the same in all scenarios (or is zero for wind energy, photovoltaic energy and bio-energy in a scenario without RES-E deployment). Two ways are used to set the generation level of a power plant type. For all technologies modeled as demand correction[1], hourly generation data are scaled in order to match the sum of the original hourly data with the aggregated data of EURELECTRIC. A second way is adding an additional constraint to the model of the form given by equation 3.19.

$$\forall j, i \in A \quad \sum_t gen_{i,j,t} = gen\_annual_{i,j} \tag{3.19}$$

   with *gen_annual* the annual historical generation in MWh and A the collection of nuclear power plants, lignite fired plants, biomass and biogas power plants, run-of-river plants and power plants based on waste.

3. Cross border transmission is difficult to calibrate as it depends on many factors. A transmission cost of 0,50 EUR/MWh is imposed to do a rough calibration of international transmission.

4. Two additional constraints are added to calibrate peak power plant types, i.e. gas turbines units and internal combustion units. The constraints impose a minimum generation level on peak power plant types (equation 3.20). Otherwise, peak power plant types are never used as no unscheduled unavailabilities occur.

$$\forall j, i \in peak \quad plants \quad \sum_t gen_{i,j,t} \geq gen\_annual_{i,j} \tag{3.20}$$

   The minimum production level is set to leave open the possibility that peak power plants produce more in scenarios without RES-E deployment. No RES-E deployment makes it more probable that peak power plants are needed to fulfill electricity demand, even without unscheduled unavailabilities.

5. In a final step, generation of coal power plants and combined cycle power plants is calibrated by adjusting rated efficiency of these power plant types, correcting fuel prices and changing power plant availabilities. Coal power plants and combined cycle power plants have one out of three possible efficiencies, i.e. 32 %, 36 % and 40 % for coal power plants and 45 %, 48 % and 51 % for

[1] Wind energy, photovoltaic energy, electric energy from cogeneration, geothermal energy and single storage energy are modeled as demand correction

combined cycle power plants. The total installed capacity is divided over the different efficiency levels in a way that departure from historical generation data is reduced and a logic evolution of the average efficiency is induced. To correct for the underproduction of coal power plants in 2009 and 2010, the coal price of EEX is replaced by the coal price of ICE, which was slightly lower at that time. The overproduction of combined cylce power plants during the same years is reduced by increasing the natural gas price with 15 % from March 20 2009 to March 19 2010. Figure 3.6 shows the coal and natural gas price for 2009 and 2010 before and after calibration. The availability of coal power plants and combined cycle power plants is adjusted per country, ranging from 60 % to 100 %.

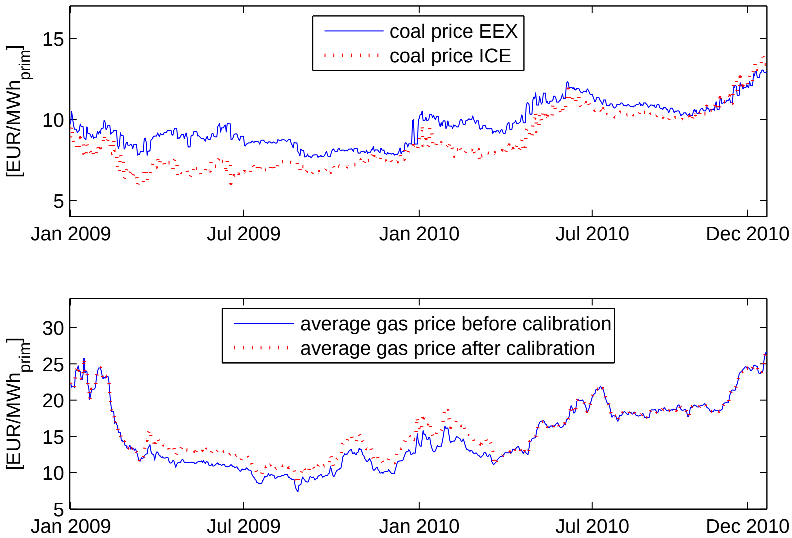



FIGURE 3.6: EEX coal price and average natural gas price for 2009 and 2010 before and after calibration of the model (daily prices).

| | coal power plants | | combined cycle power plants | |
|---|---|---|---|---|
| | $\eta_i$ | availability | $\eta_i$ | availability |
| 2007 | 34,2 % | 84,2 % | 47,3 % | 87,3 % |
| 2008 | 34,6 % | 88,4 % | 48,3 % | 82,5 % |
| 2009 | 35,9 % | 95,1 % | 48,2 % | 74,3 % |
| 2010 | 36,8 % | 81,7 % | 48,3 % | 89,8 % |

TABLE 3.3: Evolution of the rated efficiency and availability of coal power plants and combined cycle power plants (capacity weighted averages).

Table 3.4 shows a comparison between simulated electricity generation in the OBS scenario and historical generation data. It goes without saying that the output of power plant types whose generation is set, equals exactly historical generation data. This is the case for nuclear power plants, lignite based power plants and RES-E power plants (run-of-river power plants and other renewable power plants). The output of cogeneration power plants (CHP) is also set, only in the Netherlands and Denmark, some of the cogeneration output is not. This explains the deviation between historical and simulated electricity generation from cogeneration plants. The output of single storage plants is also scaled to historical data, but the output of dual storage plants is not. As mentioned before, dual storage is barely used in the model. This explains the large deviation between historical and simulated generation of storage plants. Power plant types for which the calibration is based on adjusting efficiency, availability and fuel prices, show little deviation. This is the case for coal fired power plants, natural gas fired power plants and oil fired power plants.

Table 3.5 gives a more detailed comparison between simulated and historical generation data for these latter power plants and cogeneration plants. The deviation is calculated as the aggregated simulated generation minus aggregated historical generation. The calibrated model underestimates the production of coal power plants with 1.4 % to 5.5 % and the production of combined cycle power plants with 0.7 % to 3.0 %. The reason for both deviations being negative is that dual storage is almost not used and consequently less electricity is generated compared to the historical case. The deviation in generated electricity from gas turbine units, internal combustion units and cogeneration plants is of less importance because of the small absolute deviations. It is important to bear these deviations between simulation results and historical data in mind while analyzing the results presented in this thesis.

| [TWh] | Nuclear | Coal | Lignite | Gas | Oil | RoR | RES | CHP | Storage |
|---|---|---|---|---|---|---|---|---|---|
| **2007** | | | | | | | | | |
| historical | 741 | 397 | 158 | 405 | 36 | 116 | 153 | 398 | 141 |
| simulated | 741 | 392 | 158 | 399 | 36 | 116 | 153 | 390 | 82 |
| **2008** | | | | | | | | | |
| historical | 739 | 358 | 148 | 437 | 34 | 119 | 174 | 399 | 146 |
| simulated | 739 | 343 | 148 | 428 | 37 | 119 | 174 | 399 | 86 |
| **2009** | | | | | | | | | |
| historical | 743 | 357 | 143 | 432 | 31 | 103 | 198 | 414 | 154 |
| simulated | 743 | 338 | 143 | 430 | 33 | 103 | 198 | 415 | 97 |
| **2010** | | | | | | | | | |
| historical | 747 | 357 | 137 | 419 | 27 | 125 | 227 | 429 | 166 |
| simulated | 747 | 341 | 137 | 407 | 27 | 125 | 227 | 435 | 100 |

Table 3.4: Historical electricity generation and simulated electricity generation. Aggregated annual data for 2007, 2008, 2009 and 2010.

| | Coal[1] | Gas (CC) | Gas (GT) | Oil | CHP |
|---|---|---|---|---|---|
| **2007** | | | | | |
| absolute [TWh] | -5,4 | -6,2 | 0,1 | 0 | -8,0 |
| relative [%] | -1,4 | -1,6 | 0,2 | 0 | -2,0 |
| **2008** | | | | | |
| absolute [TWh] | -14,2 | -9,2 | 0,2 | 3,4 | -0,1 |
| relative [%] | -4,0 | -2,2 | 1,0 | 10,15 | 0 |
| **2009** | | | | | |
| absolute [TWh] | -19,5 | -2,7 | 0,6 | 2,1 | 0,6 |
| relative [%] | -5,5 | -0,7 | 2,4 | 6,7 | 0,1 |
| **2010** | | | | | |
| absolute [TWh] | -15,9 | -11,8 | 0 | 0 | 5,8 |
| relative [%] | -4,5 | -3,0 | 0 | 0 | 1,4 |

Table 3.5: Deviation of simulated electricity generation from historical electricity generation. Aggregated annual data for 2007, 2008, 2009 and 2010. A negative deviation indicates that the model underestimates generation and vice versa. Relative deviation is expressed as a percentage of annual generation of this power plant type.

## 3.7 Validation of the model

In order to validate the model, a comparison between simulation results in the OBS scenario and historical data is done. Three different data sets are compared: electricity prices, $CO_2$ emissions and cross border transmission.

### 3.7.1 Electricity prices

The electricity price is determined by the model as the dual of the demand constraint (equation 3.13). The price is set by the marginal cost of the last generating power plant in the merit order, usually a coal fired, natural gas fired or oil fired power plant. Note that electricity prices discussed in this paragraph are wholesale electricity prices.

It can be expected that the model is not able to reproduce the volatility of electricity prices as only a limited number of power plants is represented in the model and dispatch of generating units is modeled in a simplified way. This is proven by figure 3.7. This figure shows that the fluctuations in historical daily prices in Belgium are not reproduced by the model. Nevertheless, it is clear that the model follows the trend of the electricity price. This insight is confirmed by comparing annual average electricity prices from Belgium, France, Germany, Netherlands, Spain and the United Kingdom (see table 3.6). Annual average prices given by the model are smaller than historical annual average prices, except for the United Kingdom in 2007 and France in 2010, but they follow the trend in historical electricity prices. The largest deviation occurs in 2007 (simulated prices on average 21 % lower), while in 2010 annual average prices match best (simulation results on average 6% lower). Price differences between countries are smaller in the model than in reality. Historical prices in each country deviate on average 3,20 EUR/MWh from the MS12 average price while in the OBS scenario this deviation is only 0,71 EUR/MWh.

The conclusion is that the model can give insights in relative differences in electricity prices between the different scenarios. The model is however not able to give accurate information on absolute price levels.

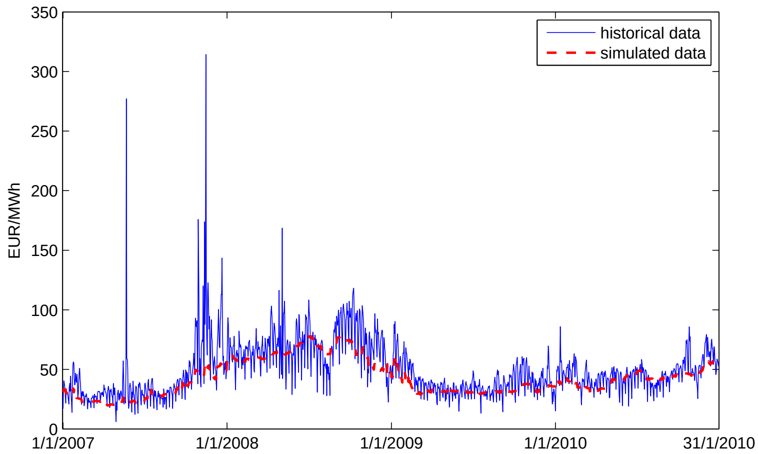



FIGURE 3.7: Historical and simulated electricity price in Belgium from 1/1/ to 31/12/2010 (daily average values) [4].

| | BE | FR | DE | NL | ES | UK |
|---|---|---|---|---|---|---|
| **2007*** | | | | | | |
| historical | 41,78 | 46,85 | 37,99 | 51,17 | 41,01 | 32,55 |
| simulated | 31,35 | 32,77 | 30,10 | 33,60 | 33,67 | 33,42 |
| **2008** | | | | | | |
| historical | 70,62 | 72,50 | 65,85 | 75,23 | 65,08 | 71,84 |
| simulated | 63,47 | 63,11 | 62,33 | 63,40 | 63,21 | 63,94 |
| **2009** | | | | | | |
| historical | 39,36 | 43,52 | 39,57 | 41,87 | 37,34 | 38,49 |
| simulated | 34,07 | 32,63 | 32,98 | 34,19 | 32,65 | 33,74 |
| **2010** | | | | | | |
| historical | 46,30 | 49,81 | 44,49 | 47,64 | 37,87 | 42,59 |
| simulated | 42,39 | 41,38 | 42,66 | 42,81 | 41,24 | 41,09 |

TABLE 3.6: Simulated and historical electricity prices for 2007, 2008, 2009 and 2010 (annual average values). *for France, the Netherlands, Spain and the United Kingdom, 2007 historical electricity prices were only available as of April 4 2007 [4][41][38].

### 3.7.2 $CO_2$ emission

It goes without saying that a good calibration based on generation data results in $CO_2$ emission data close to historical data. Moreover, it is difficult to find historical $CO_2$ emission data which are comparable with the simulation results. Emission data differ from data source to data source depending on the considered energy sectors, the considered greenhouse gasses and the way of allocating emissions to the power output of cogeneration plants.

Nevertheless, the simulated annual $CO_2$ emissions in the OBS scenario are compared with historical data (see figure 3.8). The emission data from the World Bank [43] gives $CO_2$ emissions from the electricity and heat production sector (sector 1A1a), expressed in $tCO_2$/year. EUROSTAT emission data [23] gives GHG emissions from all energy industries (sector 1A1), also including petroleum refining (sector 1A1b) and manufacture of solid fuels and other energy industries (sector 1A1c). EUROSTAT emission data is expressed in $tCO_{2,eq}$/year. EURELECTRIC emission data [19] gives $CO_2$ emissions from electricity generation expressed in $tCO_2$/year. It is remarkable that $CO_2$ emissions reported by the World Bank are larger than the EUROSTAT GHG emission data for a broader sector. This is probably due to different ways of incorporating emissions from cogeneration.

The underestimation by the model of coal power plant generation and combined cycle power plant generation leads to an underestimation of $CO_2$ emissions with 5 million $tCO_2$ to 20 million $tCO_2$. This is a minor deviation compared to the differences in emission data between the different data sources (see figure 3.8).

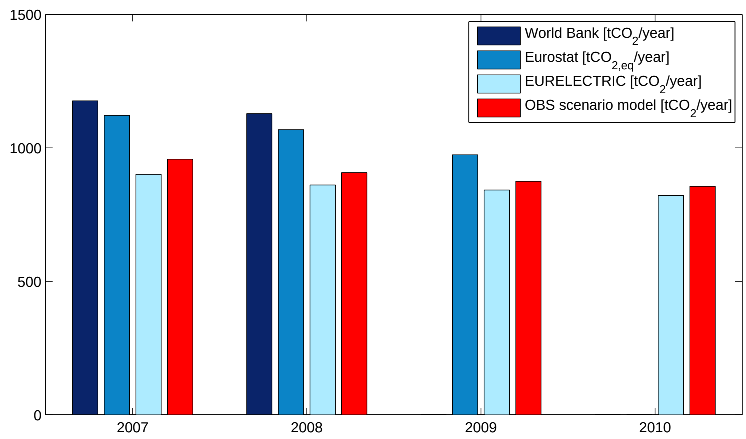



FIGURE 3.8: GHG emissions and $CO_2$ emissions in MS12 and Switzerland [43][23][19].

### 3.7.3 Cross border transmission

International transmission lines are modeled as trade based interconnections. This means that all international transport goes through lines with limited capacity, connecting the different countries. International electricity trade is assumed to be perfectly competitive. A cost of 0,50 EUR/MWh is allocated to cross border transmission.

The simulated total cross border transmission is on average 16 % smaller than historical international transmission (see table 3.7). Figure 3.9 to figure 3.12 give a detailed overview of net annual cross border transmission. For almost all connections, the model gives the correct direction of net annual cross border transmission. However, the model is not able to give an accurate picture of the amount of cross border transmission.

One remarkable aspect needs further attention. The direction of the net transmission differs for Belgium-Netherlands in 2007, 2009 and 2010, for France-Germany in 2008 and for France-Belgium in 2009 and 2010. This is possibly caused by the large wind power generation in North Germany, flowing to South Germany through the Netherlands, Belgium and France. This phenomenon can not be reproduced by the model as Germany is modeled as one node.

| | ENTSO-E [TWh] | OBS scenario [TWh] | deviation [%] |
|---|---|---|---|
| 2007 | 207 | 173 | -16 |
| 2008 | 194 | 163 | -16 |
| 2009 | 180 | 151 | -16 |
| 2010 | 186 | 158 | -15 |

TABLE 3.7: Historical and simulated annual international transmission.

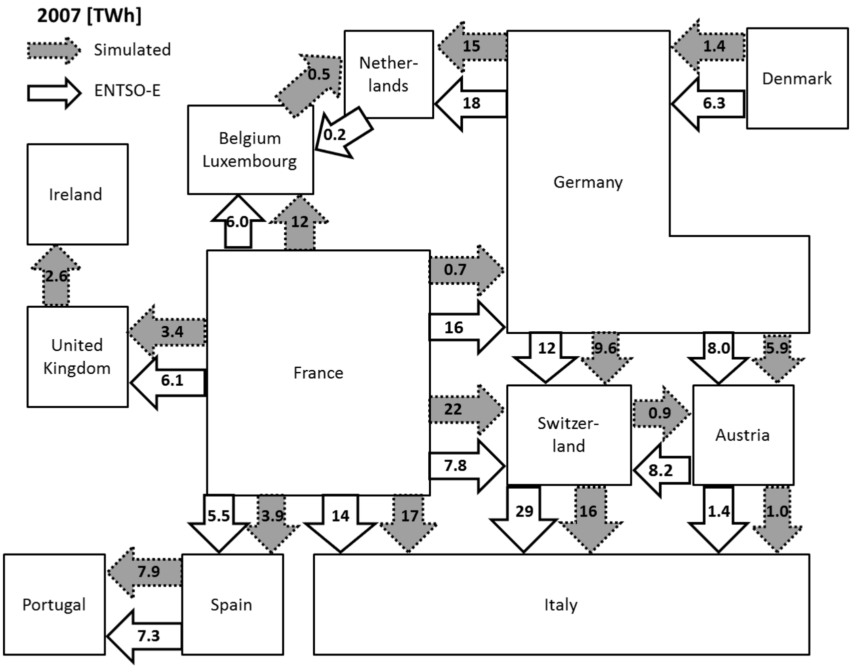



FIGURE 3.9: Overview of the net annual cross border transmission: comparison between simulation results and historical data from ENTSO-E for 2007.

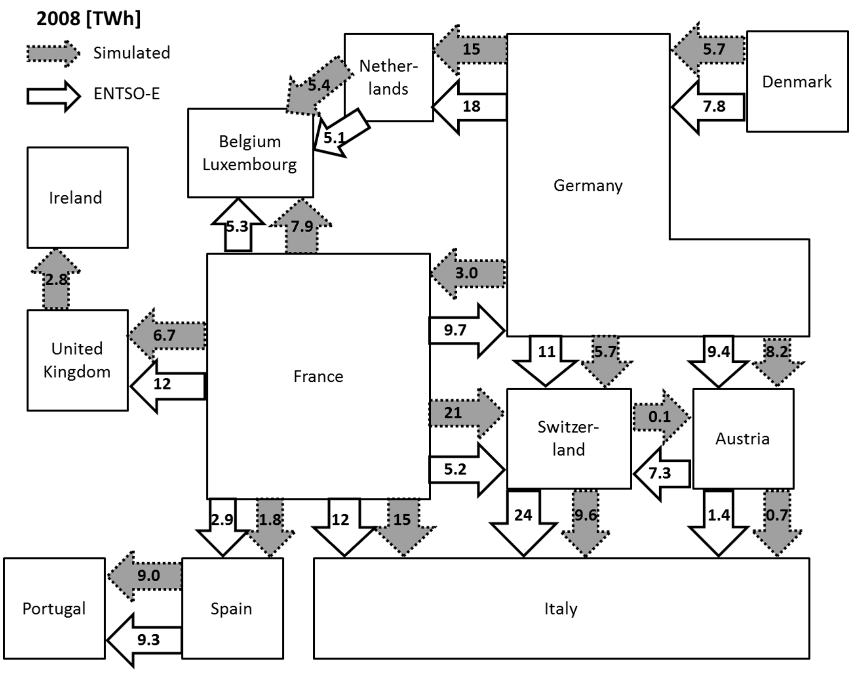



FIGURE 3.10: Overview of the net annual cross border transmission: comparison between simulation results and historical data from ENTSO-E for 2008.

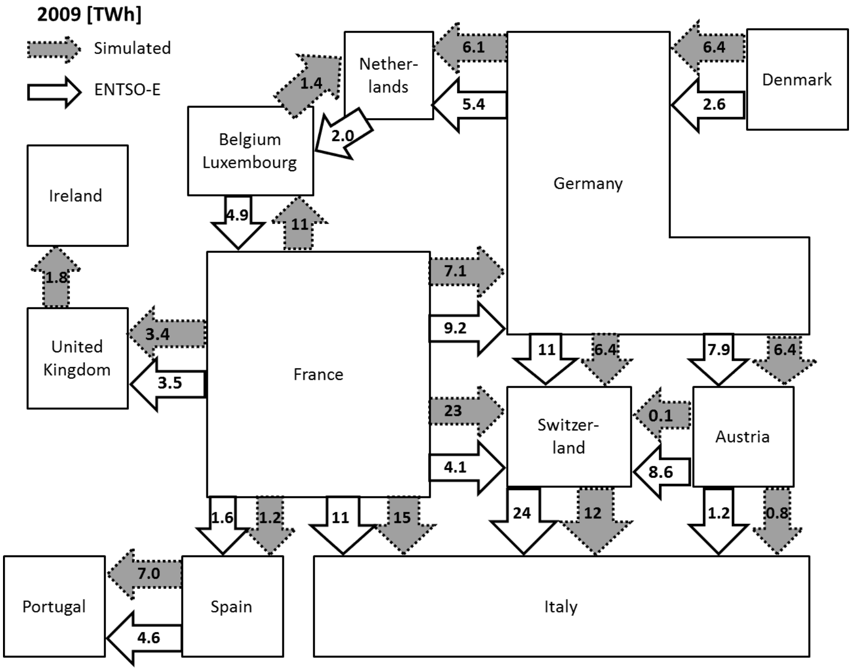



Figure 3.11: Overview of the net annual cross border transmission: comparison between simulation results and historical data from ENTSO-E for 2009.

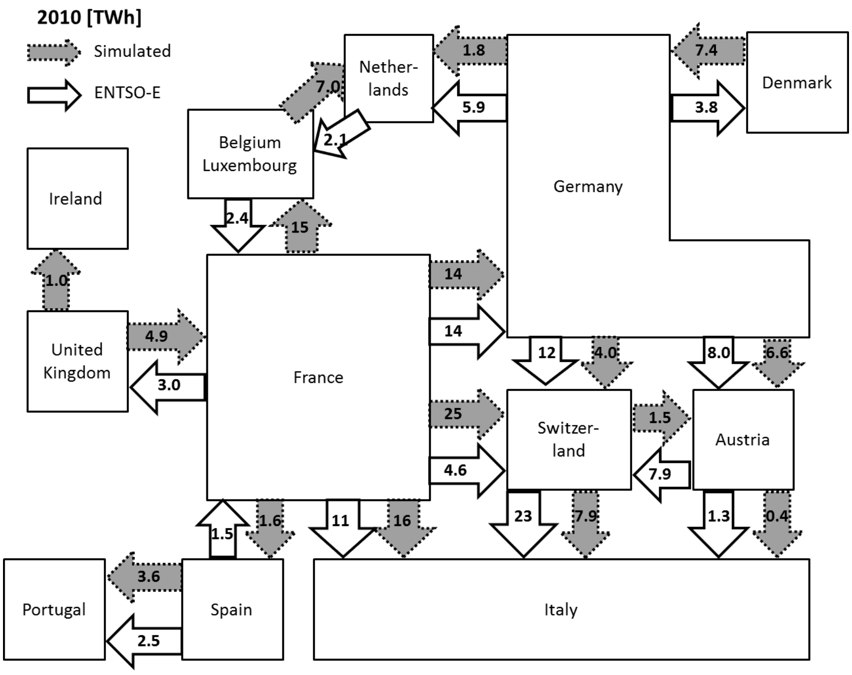



Figure 3.12: Overview of the net annual cross border transmission: comparison between simulation results and historical data from ENTSO-E for 2010.

## 3.8 Summary

The model simulates the generation of electricity in 13 European countries from 2007 to 2010. Each country is represented as a node, characterised by a power plant portfolio and an inelastic electricity demand. 23 different types of power plants are incorporated in the model. Each node is connected to neighboring nodes through an interconnection with limited capacity. The generation of electricity and trading between different countries is considered as perfectly competitive. The model determines the optimal electricity generation as the solution with minimum total generation and transmission cost. Two settings are possible with regard to RES-E deployment - with or without RES-E deployment - and three with regard to EU ETS - exogenous EUA price, $CO_2$ emission cap or none of both.

The model returns hourly generation of each power plant type in each country, hourly $CO_2$ emissions of each power plant type in each country, hourly electricity price in each country and hourly cross border transmission.

A comparison of the OBS scenario of the model with historical generation data shows that generation of coal power plants is underestimated by the model with 1,4 % to 5,5 %[2] and that generation of gas fired combined cycle power plants is underestimated with 0,7 % to 3,0 %[2]. The reason for both deviations being negative is that dual storage is barely used in the model and hence less electricity generation is needed.

Validation of the model shows that the model give an accurate picture of the historical $CO_2$ emissions in the modeled electricity sector. The model is also able to reproduce trends in annual average electricity prices but fails at giving accurate hourly prices. Moreover, the model is not able to reproduce historical cross border transmission.

As the calibration of the model is done on a yearly basis, one should be careful with comparing marginal effects between different years. Small deviations in power plant availabilities, power plant efficiencies and fuel prices can lead to relatively large deviations in marginal quantities like $CO_2$ abatement.

[2]Cogeneration plants not included.

# Chapter 4

# Impact of RES-E deployment and an EUA price on $CO_2$ emissions

This chapter discusses the impact of RES-E deployment and EU ETS on $CO_2$ emissions in the electricity sector, starting from the *ETS-price assumption.* According to the ETS-price assumption, EU ETS is modeled as an exogenous and invariable EUA price imposed on the electricity generators. This assumption implies that the electricity sector contributes very little to the $CO_2$ emissions covered by EU ETS. Therefore, a change in $CO_2$ emissions in the electricity sector is not translated into a change in EUA price.

The term *$CO_2$ abatement* is used throughout this chapter to name the difference in $CO_2$ emissions in the electricity sector between the different scenarios. This term is used for all $CO_2$ emission reductions, regardless whether they are attributable to EU ETS or RES-E deployment. To be more precise, however, only emission reductions due to EU ETS can be referred to as $CO_2$ abatement. Emission reductions in the electricity sector due to RES-E deployment and with EU ETS in place are not avoided but displaced to other ETS sectors. Therefore, emission reductions in the electricity sector due to RES-E deployment should be referred to as $CO_2$ displacement. However, for the sake of simplicity, all emission reductions are referred to as $CO_2$ abatement in this chapter.

The impact of RES-E deployment and an EUA price on $CO_2$ emissions in the electricity sector is first examined on a European scale in section 4.1 and subsequently on a national scale in section 4.2 . The EUA price and RES-E deployment influence $CO_2$ emissions by changing fuel shares, this is explained in section 4.3. Finally, the impact of each supported renewable technology separately is examined in section 4.4.

## 4.1 European scale

Figure 4.1 shows $CO_2$ emissions in the electricity sector in the 12 European Member States included in the analysis under the different scenarios. It is evident that a scenario without EU ETS and without RES-E deployment (NOPOL scenario) results in the largest $CO_2$ emissions, whereas the observed scenario with both policy instruments in place (OBS scenario), results in the lowest $CO_2$ emissions. In 2007, the EUA price was so low that the effect of EU ETS is almost negligible and all $CO_2$ abatement is attributable to RES-E deployment. It is also clear from the figure that in 2008, 2009 and 2010, RES-E deployment and EU ETS contribute more or less equally to $CO_2$ abatement. RES-E deployment has a slightly larger impact on $CO_2$ emissions than EU ETS in 2009 and 2010, whereas the opposite is true for 2008.

$CO_2$ emissions in the NOPOL scenario show a remarkable evolution. One would expect that $CO_2$ emissions steadily rise as electricity demand rises, but $CO_2$ emissions are significantly higher in 2008 and 2009 than in 2007 and 2010. This can be partly explained by deviations in calibration parameters between the different years. Table 3.3 (see page 31) shows that 2008 and 2009 are characterized by high coal power plant availabilities and low gas fired combined cycle availabilities.

Figure 4.2 shows the $CO_2$ abatement due to RES-E deployment and the EUA price. Total $CO_2$ abatement is the difference in $CO_2$ emissions between the NOPOL scenario and the OBS scenario. Based on the emissions in the ETS scenario and RES scenario, it is possible to estimate $CO_2$ abatement attributable to each policy instrument. Note that the abatement caused by a policy instrument depends on whether or not the other policy instrument is in place. This phenomenon is an example of interaction between EU ETS and RES-E deployment. In figure 4.2, the left bar of each year represents the case where first EU ETS is introduced in absence of RES-E deployment, followed by the introduction of RES-E deployment with EU ETS already in place. The right bar of each year represents the reverse case, i.e. the introduction of RES-E deployment without EU ETS in place, followed by the introduction of EU ETS with RES-E deployment already in place. It becomes clear from figure 4.2 that this interaction effect between EU ETS and RES-E deployment is positive, meaning that the $CO_2$ abatement caused by the introduction of one policy instrument is larger when the other policy instrument is already in place. This positive interaction effect is more explicit in 2009 and 2010.

In 2007, total $CO_2$ abatement due to RES-E deployment and EU ETS was 106 million $tCO_2$ or 11 % of $CO_2$ emissions in the OBS scenario. This $CO_2$ abatement was mainly caused by RES-E injections as the EUA price was very low at that time. 2008, 2009 and 2010 show a different trend. Total $CO_2$ abatement during these years was respectively 234 million $tCO_2$, 265 million $tCO_2$ and 221 million $tCO_2$ or 26 %, 30 % and 26 % of total $CO_2$ emissions in the OBS scenario. The decrease in $CO_2$ abatement in 2010 compared to 2009, despite a stable EUA price and a further increase of RES-E injections, is caused by the strong decline of $CO_2$ emissions in the NOPOL scenario (see figure 4.1). On average 48 % of the $CO_2$ abatement in

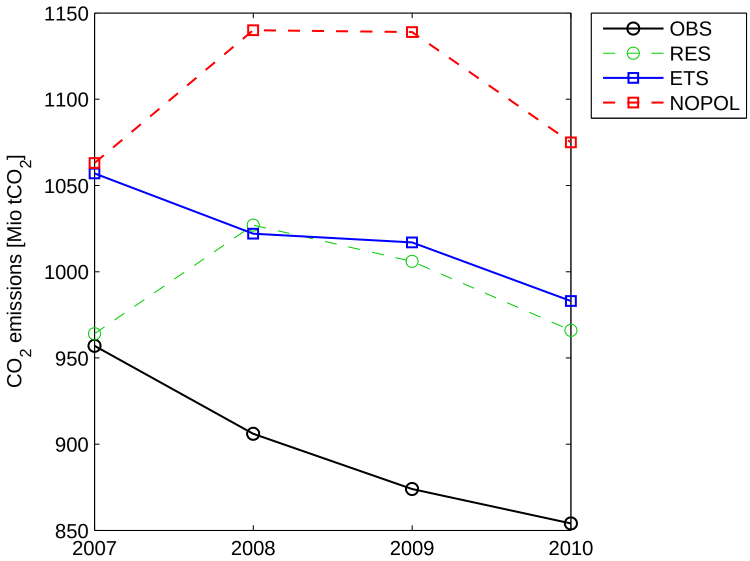



FIGURE 4.1: $CO_2$ emissions in the electricity sector for MS12 in the different scenarios.

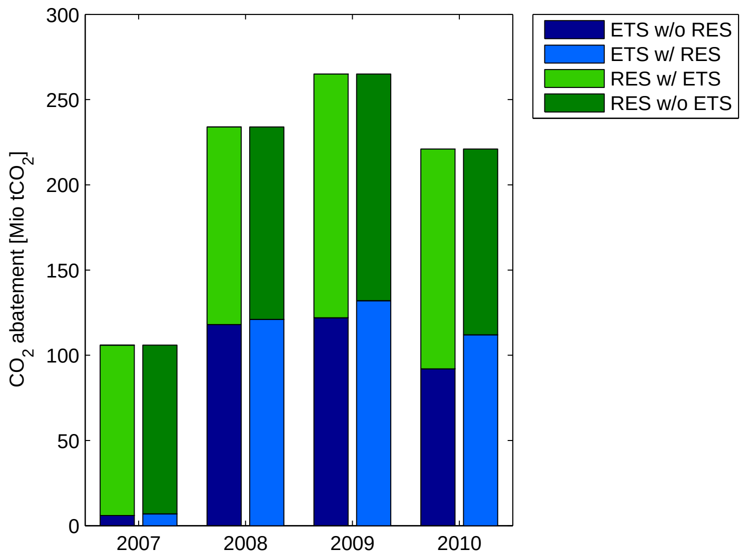



FIGURE 4.2: Total annual $CO_2$ abatement in MS12 and allocation of this abatement to RES-E deployment and EU ETS.

2008-2010 was caused by EU ETS and 52 % by RES-E deployment. The positive interaction effect increases the effect of a policy instrument with 1 to 20 million $tCO_2$/year or 1 to 9 %-points when it is introduced with the other instrument already in place. The key results are summarized in table 4.1.

Appendix A.1 and appendix A.2 give an extended overview of $CO_2$ emissions in the different scenarios and $CO_2$ abatement.

| | $CO_2$ abatement | | Impact ETS [Mio $tCO_2$] | | Impact RES-E [Mio $tCO_2$] | |
|---|---|---|---|---|---|---|
| | Mio $tCO_2$ | [%] | w/o RES-E | w/ RES-E | w/o ETS | w/ ETS |
| 2007 | 106 | 11 | 6 | 7 | 99 | 100 |
| 2008 | 234 | 26 | 118 | 121 | 113 | 116 |
| 2009 | 265 | 30 | 122 | 132 | 133 | 143 |
| 2010 | 221 | 26 | 92 | 112 | 109 | 129 |

Table 4.1: Total annual $CO_2$ abatement in MS12 and allocation of this abatement to RES-E deployment and EU ETS. Relative $CO_2$ abatement is expressed as percentage of $CO_2$ emissions in the OBS scenario.

## 4.2 National scale

The impact of RES-E deployment and EU ETS on national $CO_2$ emissions consists of the combination of two effects. The first effect is a change in electricity generation per country and the concomitant shift in annual net cross border transmission. The second effect is a decline in $CO_2$ intensity of electricity generation in each country. The analysis presented in this section is made up of three steps. First, the change in cross border transmission is examined. Subsequently, the change in $CO_2$ intensity is discussed and in a final step, these two effects are brought together to assess the net effect of the EUA price and RES-E deployment on national $CO_2$ emissions.

Table 4.2 gives an overview of the change in annual net cross border transmission when EU ETS and/or RES-E deployment are introduced. If export increases or import decreases when a policy instrument is introduced, electricity generation is shifted towards this country due to the introduction of that policy instrument. Contrariwise, if export decreases or import increases when a policy instrument is introduced, electricity generation is shifted away from this country due to the introduction of that policy instrument. If EU ETS is introduced, starting from the RES scenario, electricity generation is shifted from France and Germany to almost all neighboring countries (Belgium, Ireland, Italy, the Netherlands, Spain and the United Kingdom). Generation in Austria, Denmark and Portugal barely changes. If RES-E deployment is introduced, starting from the ETS scenario, electricity generation shifts from Belgium, Italy, the Netherlands and the United Kingdom towards Austria, Denmark and Germany. Generation in France, Ireland, Portugal and Spain is barely influenced by the introduction of RES-E deployment. If both EU ETS and RES-E deployment are introduced, starting from the NOPOL scenario, electricity generation shifts from mainly France and to a lesser extent the Netherlands and the United Kingdom

| | Introduction of ETS | | Introduction of RES-E | | Introduction of ETS and RES-E | |
|---|---|---|---|---|---|---|
| | [TWh] | [%] | [TWh] | [%] | [TWh] | [%] |
| AT | -0,3 | -0,5 | 4,0 | 6,5 | 3,8 | 6,2 |
| BE | 6,9 | 7,6 | -2,7 | -3,0 | 1,2 | 1,3 |
| DK | -0,4 | -1,3 | 6,3 | 18,2 | 6,1 | 17,8 |
| FR | -23,9 | -4,9 | 1,8 | 0,4 | -16,9 | -3,5 |
| DE | -20,4 | -3,6 | 17,3 | 3,0 | 6,4 | 1,1 |
| IE | 1,3 | 4,6 | 0,0 | 0,0 | 1,0 | 3,7 |
| IT | 15,3 | 4,6 | -11,4 | -3,4 | 0,6 | 0,2 |
| NL | 10,9 | 9,4 | -8,7 | -7,5 | -3,2 | -2,8 |
| PT | -0,9 | -1,7 | 0,8 | 1,4 | 0,3 | 0,6 |
| ES | 5,9 | 2,1 | -0,8 | -0,3 | 3,3 | 1,2 |
| UK | 5,7 | 1,6 | -7,3 | -2,0 | -3,4 | -0,9 |

TABLE 4.2: Average change in annual net cross border transmission between the different scenarios for 2007-2010. Changes with a positive sign indicate increased generation due to the introduction of the policy instrument(s), i.e. increased export or decreased import. Changes with a negative sign indicate decreased generation due to the introduction of the policy instrument(s), i.e. decreased export or increased import. Relative changes are expressed as a percentage of the aggregated national demand. 2007 is not considered in the calculation of changes due to the introduction of EU ETS as EUA price was negligible at that time. Luxembourg is not included as no $CO_2$ abatement occurs in Luxembourg.

towards all other countries. Net cross border transmission gives however only a first indication on the changes in generation per country. A more thorough understanding of the influence of cross border transmission requires an analysis on hourly basis. Importing electricity to replace $CO_2$ intensive coal power plants and exporting later on the same amount of electricity generated by less $CO_2$ intensive combined cycle power plants does not result in a net change in cross border transmission, but it clearly has an impact on national $CO_2$ emissions.

Besides a shift in electricity generation per country, EU ETS and RES-E deployment also cause a change in $CO_2$ intensity of electricity generation in each country. Figure 4.3 shows the impact of EU ETS and RES-E deployment on $CO_2$ intensity. Total $CO_2$ intensity of electricity generation in MS12 decreases by 77 $tCO_2/GWh$, from 407 $tCO_2/GWh$ to 327 $tCO_2/GWh$. Denmark and Germany show a way larger decline in $CO_2$ intensity, mainly due to significant RES-E injections. $CO_2$ intensity also decreases more than average in Ireland, Portugal, Spain and the United Kingdom. Austria, Belgium, France, Italy and the Netherlands demonstrate a smaller than average decline in $CO_2$ intensity.

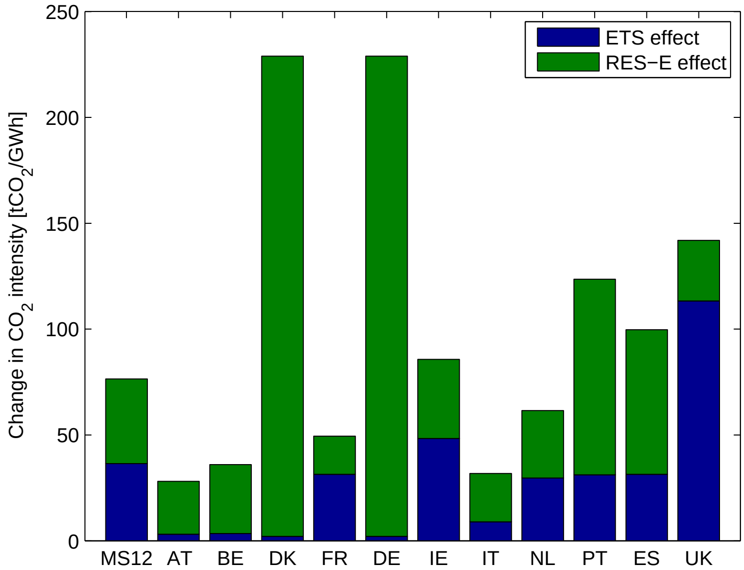



FIGURE 4.3: Decrease in $CO_2$ intensity of electricity generation and allocation of total decrease to EU ETS and RES-E deployment. $CO_2$ intensity is calculated as aggregated $CO_2$ emissions from 2007 to 2010 divided by aggregated electricity generation from 2007 to 2010. Luxembourg is not included as no $CO_2$ abatement occurs in Luxembourg.

In a final step, the changes in electricity generation per country and $CO_2$ intensity are brought together to determine $CO_2$ abatement per country, see table 4.3. Germany, the United Kingdom, Spain and France show by far the largest $CO_2$ abatement. In France, this abatement is mainly due to a decline in generation whereas in Germany and Spain the decline in $CO_2$ intensity is the main driver of $CO_2$ abatement. In the United Kingdom, both a decline in electricity generation and a decline in $CO_2$ intensity contribute to the $CO_2$ abatement. For most countries, $CO_2$ abatement evolves in a way similar to the aggregated figure (see figure 4.2). Abatement in 2007 is lower than abatement in 2008, 2009 and 2010. Only Denmark shows a larger $CO_2$ abatement in 2007 compared to 2008, 2009 and 2010. Denmark is in the OBS scenario a net exporter to Germany. In the ETS scenario, Denmark becomes a net importer in 2008, 2009 and 2010 but it stays a net exporter in 2007. This means that in 2007, RES-E generation is replaced by internal generation whereas in the other years, RES-E generation is replaced by German generation. This explains the large $CO_2$ abatement in 2007.

In 2007, almost all $CO_2$ abatement is attributable to RES-E deployment because of a very low EUA price. In 2008, 2009 and 2010, both policy instruments are responsible for $CO_2$ abatement. One can divide the countries in four groups based on the impact of RES-E and EU ETS on $CO_2$ emissions:

| [Mio $tCO_2$] | AT | BE | DK | FR | DE | IE | IT | NL | PT | ES | UK |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | **2007** | | | | | |
| $CO_2$ abatement | 0,1 | 2,7 | 12,1 | 7,0 | 33,3 | 1,0 | 8,0 | 9,5 | 2,8 | 16,9 | 12,4 |
| ETS w/o RES | 0 | 0 | 0,4 | 1,1 | 2,0 | 0,1 | -0,5 | 0,1 | 0,1 | 0,6 | 1,7 |
| ETS w/ RES | 0 | 0 | 0,5 | 1,6 | 1,8 | 0,1 | -0,5 | 0,2 | 0,2 | 0,6 | 2,7 |
| RES w/o ETS | 0,1 | 2,7 | 11,6 | 5,4 | 31,5 | 0,9 | 8,0 | 9,3 | 2,6 | 16,3 | 9,7 |
| RES w/ ETS | 0,1 | 2,7 | 11,7 | 5,9 | 31,3 | 0,9 | 8,0 | 9,4 | 2,7 | 16,3 | 10,7 |
| | | | | | | **2008** | | | | | |
| $CO_2$ abatement | 0,5 | 2,0 | 0,5 | 38,4 | 87,7 | 2,2 | 4,8 | 7,0 | 5,3 | 25,8 | 59,2 |
| ETS w/o RES | 0,2 | -0,8 | 0,2 | 30,9 | 41,7 | 1,3 | -6,2 | -1,2 | 0,7 | 7,1 | 44,4 |
| ETS w/ RES | 0,4 | -1,0 | 0,1 | 26,1 | 38,0 | 1,4 | -3,2 | 0,1 | 1,8 | 9,2 | 47,3 |
| RES w/o ETS | 0,1 | 3,0 | 0,4 | 12,3 | 49,7 | 0,8 | 8,0 | 6,9 | 3,5 | 16,6 | 11,9 |
| RES w/ ETS | 0,3 | 2,8 | 0,3 | 7,5 | 46,0 | 0,9 | 11,0 | 8,2 | 4,6 | 18,7 | 14,8 |
| | | | | | | **2009** | | | | | |
| $CO_2$ abatement | 0,5 | 2,4 | 0,7 | 41,4 | 87,1 | 1,7 | 10,1 | 7,3 | 7,5 | 36,7 | 70,5 |
| ETS w/o RES | 0,2 | -1,2 | 0 | 25,4 | 31,6 | 0,6 | -2,3 | 0,2 | 2,4 | 12,9 | 52,8 |
| ETS w/ RES | 0,3 | -1,4 | 0,3 | 22,6 | 37,4 | 0,8 | -1,6 | -0,8 | 3,7 | 15,4 | 55,5 |
| RES w/o ETS | 0,2 | 3,8 | 0,4 | 18,8 | 49,7 | 0,9 | 11,7 | 8,1 | 3,8 | 21,3 | 15,0 |
| RES w/ ETS | 0,3 | 3,6 | 0,7 | 16,0 | 55,5 | 1,1 | 12,4 | 7,1 | 5,1 | 23,8 | 17,7 |
| | | | | | | **2010** | | | | | |
| $CO_2$ abatement | 0,4 | 3,7 | 2,0 | 29,3 | 48,5 | 1,2 | 14,7 | 9,3 | 7,0 | 31,0 | 72,9 |
| ETS w/o RES | 0,2 | -0,6 | 0 | 20,5 | 14,7 | 0,2 | -3,8 | -0,2 | 2,1 | 6,1 | 53,0 |
| ETS w/ RES | 0,3 | -0,9 | 0,7 | 24,9 | 26,7 | 0,4 | -4,6 | -1,2 | 2,9 | 7,5 | 54,6 |
| RES w/o ETS | 0,1 | 4,6 | 1,3 | 4,4 | 21,8 | 0,8 | 19,3 | 10,5 | 4,1 | 23,5 | 18,3 |
| RES w/ ETS | 0,2 | 4,3 | 2,0 | 8,8 | 33,8 | 1,0 | 18,5 | 9,5 | 4,9 | 24,9 | 19,9 |
| | | | | | | **2007-2010** | | | | | |
| $CO_2$ abatement | 1,5 | 10,8 | 15,3 | 116,1 | 256,6 | 6,1 | 37,6 | 33,1 | 22,6 | 110,4 | 215,0 |

TABLE 4.3: $CO_2$ abatement in every country due to RES-E deployment and EU ETS. Luxembourg is not included as no $CO_2$ abatement occurs in Luxembourg.

- **EU ETS main impact.** In the United Kingdom and France, EU ETS has the largest impact on $CO_2$ emissions with on average respectively 76 % and 69 % of the abatement attributable to EU ETS. The large effect of ETS in France can be explained by a change in export. France has a large capacity of coal power plants, only needed to fulfill French peak demand. Without EU ETS, these coal power plants are more frequently used to export electricity. This results in an increase in export from France of 24 TWh/year or 4,9 % of the total demand in absence of EU ETS. Note that France has, due to large nuclear capacity, low absolute $CO_2$ emissions, resulting in large relative effects. In the United Kingdom, the impact of EU ETS translates into a fuel shift from coal to gas, making electricity generation less $CO_2$ intensive (see figure 4.3) In the OBS scenario, coal share varies between 29 % and 36 % and gas share varies between 42 % and 50 %. In absence of EU ETS, coal share increases up to 59 % and gas share falls down to 18 %. Note also that both countries have low RES-E production (see table 2.2 on page 10).

- **RES-E deployment main impact.** In Spain, Portugal and Denmark, RES-E injections are responsible for respectively 69 %, 66 % and 80 % of $CO_2$ abatement. This is mainly due to the large RES-E production in these countries (see table 2.2 on page 10).

- **Equal impact of EU ETS and RES-E deployment.** In Austria, Germany and Ireland, both policy instruments contribute more or less equally to $CO_2$ abatement.

- **Negative EU ETS impact.** Belgium, the Netherlands and Italy show negative EU ETS contribution to $CO_2$ abatement, meaning that the introduction of EU ETS results in an increase in $CO_2$ emissions due to a change in import. Electricity generation in these countries increases with respectively 7 TWh/year, 11 TWh/year and 15 TWh/year when EU ETS is introduced. This increase in generation causes higher $CO_2$ emissions than in a scenario without ETS. The extra generation in these countries is mainly due to a reduction in import from France.

In conclusion, a small note on the interaction effect between EU ETS and RES-E deployment regarding $CO_2$ abatement in the electricity sector. In the 44 cases considered[1], 34 indicate positive interaction and 10 indicate negative interaction. Although the aggregated interaction effect over all countries is positive, on a national level the interaction effect can be negative as well. This interaction effect is discussed further in detail in chapter 6.

An extended overview of $CO_2$ emissions and $CO_2$ abatement for all countries can be found in respectively appendix A.1 and appendix A.2. Net cross border transmissions data are given in appendix A.3 and $CO_2$ intensity data in appendix A.4.

## 4.3 Impact of RES-E and ETS on fuel shares

This section takes a closer look at the fuel shares in the different scenarios. Short term $CO_2$ abatement is the direct consequence of changes in fuel shares caused by the EUA price and RES-E deployment. Fuel shares in MS12, Germany, Spain and the United Kingdom are examined.

EU ETS reduces the coal share in MS12 with 0,4 to 9,3 %-points but increases gas share with 0,4 to 9,5 %-points. The changes in fuel shares are caused by fuel switching. As the EUA price makes coal power plants more expensive in relation to natural gas power plants, natural gas will be more often preferred to coal. RES-E

[1] 11 countries, 4 years

injections decrease coal share and gas share in MS12 with 0,9 to 4,1 %-points and 4,1 to 8,3 %-points, respectively. RES-E injections have a larger effect on gas share than on coal share. RES-E replaces conventional generation starting with the most expensive generating power plant, being most of the time natural gas power plants. Unlike EU ETS, RES-E deployment decreases both fuel shares and hence does not discriminate according to the carbon content of the fuels [41].

$CO_2$ abatement attributable to EU ETS and RES-E deployment can be estimated based on the changes in fuel shares. $CO_2$ abatement attributable to RES-E deployment without interaction with EU ETS follows from

$$CO_2\_abatement = \left( \frac{|R_{C,N}| * EF_C}{\eta_C} + \frac{|R_{G,N}| * EF_G}{\eta_G} \right) * gen_{tot} \tag{4.1}$$

and in the case of interaction with EU ETS

$$CO_2\_abatement = \left( \frac{|R_{C,I}| * EF_C}{\eta_C} + \frac{|R_{G,I}| * EF_G}{\eta_G} \right) * gen_{tot} \tag{4.2}$$

with $R$ the change in fuel share in %-points due to RES-E deployment, $C$ and $G$ referring to respectively coal and gas, $N$ and $I$ referring to respectively without interaction and with interaction, $EF$ the emission factor in $tCO_2/MWh_{prim}$, $\eta$ the rated efficiency of the power plant type and $gen_{tot}$ the aggregated electricity generation in MWh. Analogously, $CO_2$ abatement attributable to EU ETS follows from

$$CO_2\_abatement = \left( \frac{|E_{C,N}| * EF_C}{\eta_C} - \frac{|E_{G,N}| * EF_G}{\eta_G} \right) * gen_{tot} \tag{4.3}$$

$$CO_2\_abatement = \left( \frac{|E_{C,I}| * EF_C}{\eta_C} - \frac{|E_{G,I}| * EF_G}{\eta_G} \right) * gen_{tot} \tag{4.4}$$

respectively for the scenario without and with interaction with RES-E deployment. $E$ is the change in fuel share in %-points due to EU ETS. Figure 4.4 shows how $R$ is determined.

If the method described above is applied to the fuel shares presented in figure 4.5, it becomes again clear that EU ETS and RES-E have an equal impact on $CO_2$ emissions in MS12. In the United Kingdom, EU ETS has a larger impact than RES-E deployment. In Spain, the opposite holds and in Germany both policy instruments have more or less equal impact.

An overview of coal share and gas shares for each countries and each scenario can be found in appendix A.5.

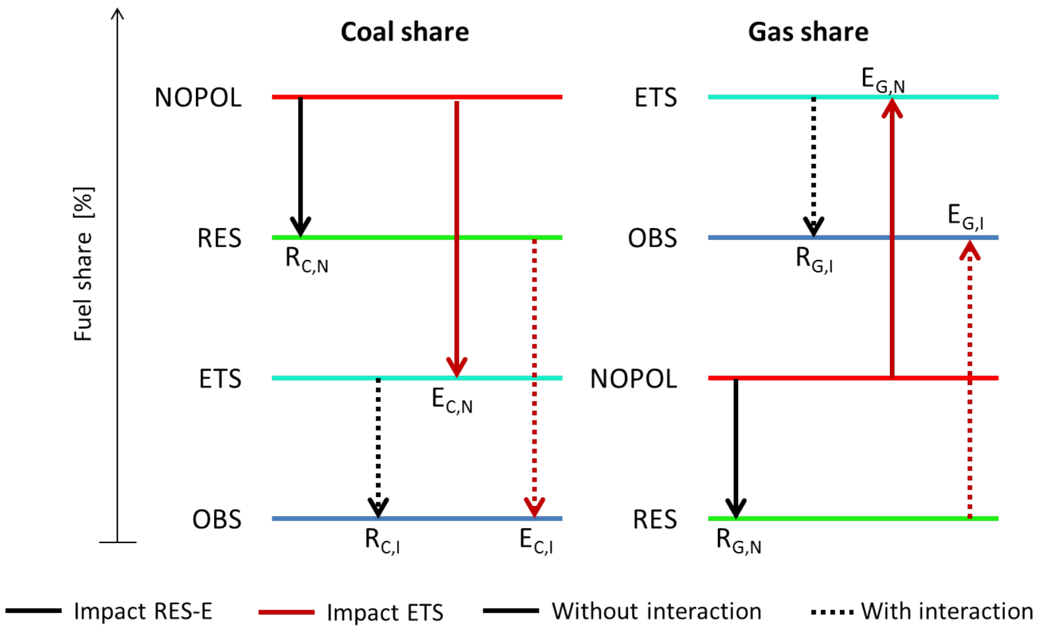
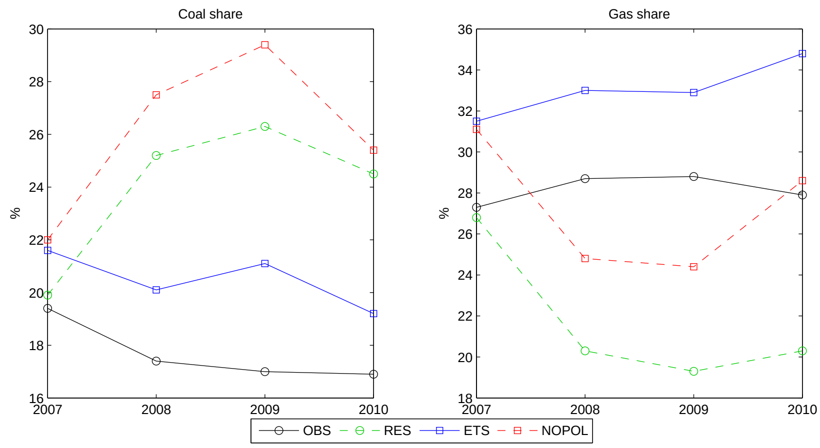
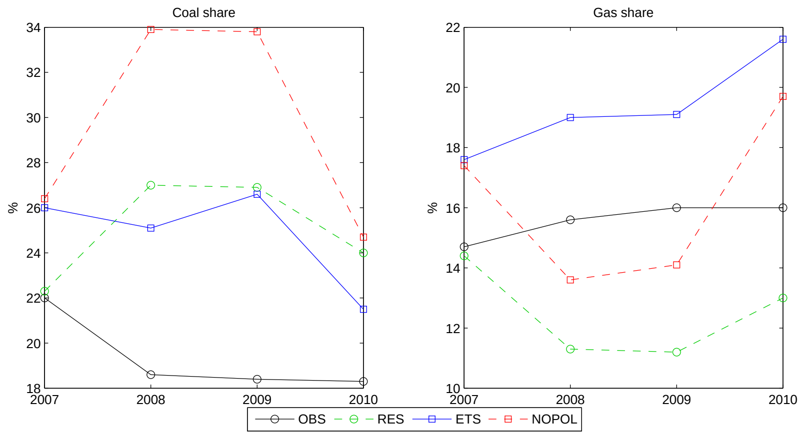


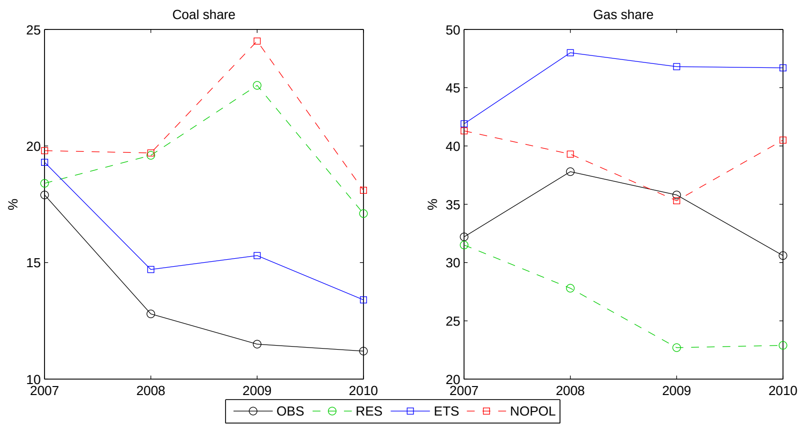

FIGURE 4.4: Schematic example of impact of RES-E deployment and EU ETS on coal share and gas share.



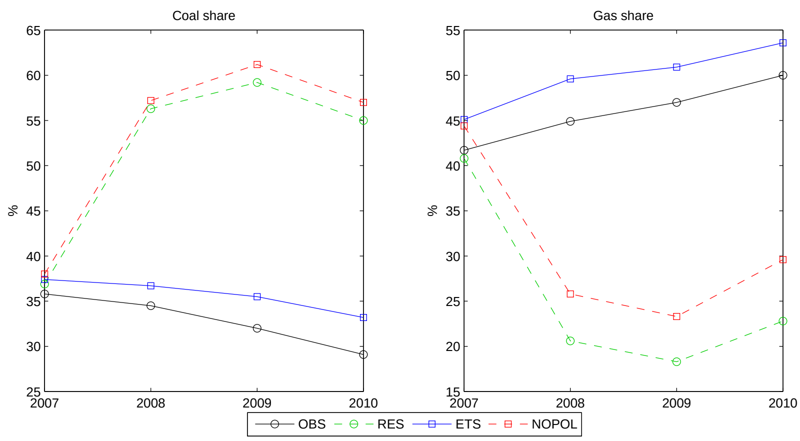

(a) MS12




(a) Germany




(b) Spain




(c) United Kingdom

FIGURE 4.5: Coal share and gas share in electricity generation. Coal share and gas share include cogeneration plants.

## 4.4 Impact of different types of RES-E

In a final step, the impact of each supported renewable electricity source is examined. Over the considered period, the capacity of all types of RES-E increased. Wind energy generation increased from 99 TWh in 2007 to 136 TWh in 2010, solar energy generation rose from 4 TWh in 2007 to 20 TWh in 2010 and electricity generation from biomass and biogas increased from 52 TWh to 70 TWh (see left panel of figure 4.6a).

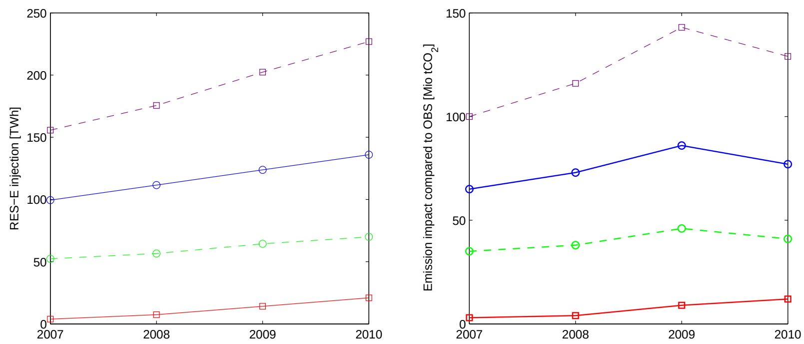
The impact of wind energy, solar energy and bio-energy on $CO_2$ emissions in MS12 is presented in the right panel of figure 4.6a. The impact on emissions follows the same pattern as RES-E injections, although some variations are noticeable. From 2008 to 2009, RES-E injections increased by 12 % whereas the $CO_2$ abatement due to these injections increased by 27 %. The larger $CO_2$ abatement per injected unit of renewable energy is due to a smaller gap in marginal generation cost between coal power plants and gas power plants. In 2008, average marginal generation cost of a coal power plant is 2,7 EUR/MWh lower than the marginal generation cost of a gas power plant. In 2009, this cost gap is narrowed to on average 1,2 EUR/MWh. Consequentely, relatively more coal power plants are pushed out of the merit order by RES-E injections in 2009, resulting in a larger impact on $CO_2$ emissions. A second remarkable deviation between RES-E injections and impact on $CO_2$ emissions is that, despite a further increase in RES-E injections in 2010, $CO_2$ abatement decreases from 2010 to 2009. This is due to differences in calibration parameters between 2009 and 2010, resulting in un underestimation of the usage of coal power plants in 2010.

The same analysis is done for the two countries with the highest RES-E injections, i.e. Germany and Spain (see figure 4.6b for Germany and 4.6c for Spain). Both countries show a pattern similar to the aggregated pattern for MS12.

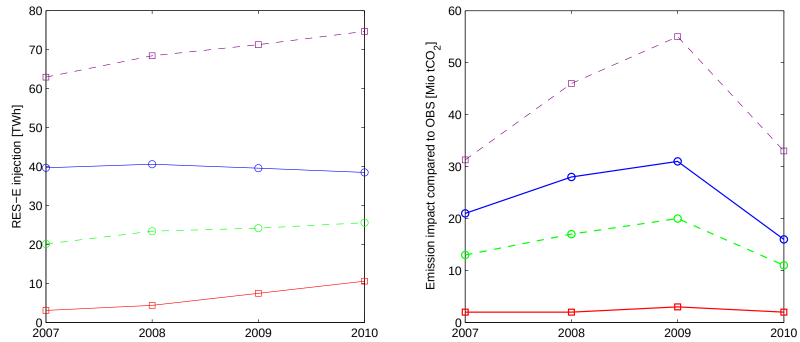
From figure 4.6, it can be derived that the aggregated impact of each renewable source separately does not equal the impact of all supported RES-E operating at the same time. It becomes clear that there is not only interaction between EU ETS and RES-E deployment, but also between support mechanisms for different renewable sources of electricity.

As RES-E injections cause $CO_2$ abatement, they can be considered as power plants with a negative $CO_2$ intensity. Unlike conventional power plants, $CO_2$ intensity of RES-E is not a characteristic of the power plant itself but it is determined by the whole power plant portfolio. Table 4.4 gives an overview of the $CO_2$ intensity of different renewable sources in MS12. The $CO_2$ intensity varies from year to year and from scenario to scenario. The average negative $CO_2$ intensity of renewable electricity sources within the European electricity sector from 2007 to 2010 was 0,647 $tCO_2$/MWh.

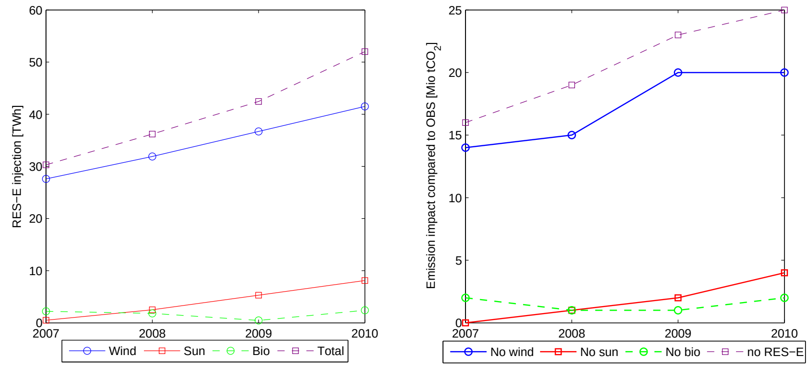
Appendix A.6 gives an overview of the impact of different types of RES-E on $CO_2$ emissions for each country.




(a) MS12




(b) Germany




(c) Spain

FIGURE 4.6: Historic RES-E injection from wind energy, bio-energy and solar energy and the impact of these RES-E injections on $CO_2$ emissions expressed as difference in $CO_2$ emissions with the OBS scenario.

| | RES-E injection [TWh] | $CO_2$ abatement [Mio $tCO_2$] | | $CO_2$ intensity [$tCO_2$/MWh] | |
|---|---|---|---|---|---|
| | | w/int. | w/o int. | w/ int. | w/o int. |
| 2007 | 151 | 99 | 100 | 0,656 | 0,662 |
| 2008 | 172 | 113 | 116 | 0,657 | 0,674 |
| 2009 | 193 | 133 | 143 | 0,689 | 0,741 |
| 2010 | 216 | 109 | 129 | 0,505 | 0,597 |

Table 4.4: RES-E injections, $CO_2$ abatement and $CO_2$ intensity in MS12. Abatement and intensity for scenarios with interaction and without interaction.

## 4.5 Summary

The aim of this master thesis is to quantify the impact of EU ETS and RES-E deployment on $CO_2$ emissions in the electricity sector and on the EUA price. EU ETS caps the $CO_2$ emissions from all ETS sectors, including the electricity sector, and puts a price on $CO_2$ emissions. RES-E deployment displaces $CO_2$ emissions from the electricity sector to other ETS sectors and reduces at the same time the EUA price.

This chapter quantifies the impact of EU ETS and RES-E deployment on $CO_2$ emissions in the electricity sector, starting from the *ETS-price assumption*. This assumption means that the EUA price is considered as an exogenous parameter and the impact of RES-E deployment is fully expressed as $CO_2$ displacement to ETS sectors excluding the electricity sector. The ETS-price assumption implies that the impact on $CO_2$ emissions of RES-E deployment is overestimated as the effect of RES-E deployment on the EUA price is neglected.

In 2007, $CO_2$ abatement in MS12 due to RES-E deployment and EU ETS is 106 million $tCO_2$ or 11 % of historical $CO_2$ emissions. In 2008, 2009 and 2010, $CO_2$ abatement increased to respectively 234 million $tCO_2$, 265 million $tCO_2$ and 221 million $tCO_2$ or 26 %, 30 % and 26 % of historical $CO_2$ emissions. In 2007, $CO_2$ emission reduction is mainly caused by RES-E deployment because of the very low EUA price at that time. In 2008, 2009 and 2010, RES-E deployment and EU ETS contributed more or less equally to $CO_2$ emission reductions. On average 48 % of the $CO_2$ abatement in 2008-2010 is caused by EU ETS and 52 % by RES-E deployment.

On a national level, $CO_2$ abatement due to RES-E deployment and EU ETS follows from a change in electricity generated per country and a change in $CO_2$ intensity of electricity generation in each country. The analysis shows that the introduction of EU ETS moves generation mainly from France and Germany to Italy, the Benelux, Spain, Ireland and the United Kingdom. The introduction of RES-E deployment moves generation mainly from Italy and the Netherlands to Germany and Denmark. Improvement of $CO_2$ intensity due to RES-E deployment and EU ETS is largest in Denmark, Germany, Portugal, Spain and the United Kingdom. In conclusion, most $CO_2$ emission reduction takes place in Germany, France, Spain and the United

Kingdom.

One can divide Western and Southern Europe in four groups based on relative impact of RES-E deployment and RES-E. In France and the United Kingdom, most $CO_2$ abatement is attributable to EU ETS. In Spain, Portugal and Denmark RES-E deployment is responsible for most of the $CO_2$ abatement due to high RES-E injections. Austria, Germany and Ireland show equal impact of RES-E deployment and EU ETS. Finally, Belgium, the Netherlands and Italy indicate a negative EU ETS impact. This means that $CO_2$ emissions in these countries increase when EU ETS is introduced due to a strong drop in imported electricity from France.

Fuel shares changes as expected. EU ETS reduces coal share but increases gas share. RES-E deployment reduces both coal share and gas share. Wind energy is the form of renewable energy with largest emission impact followed by bio-energy. The importance of solar energy steadily increases, but stays limited.

RES-E deployment and EU ETS interact with each other with regard to $CO_2$ emission reductions in the electricity sector, meaning that the impact of one policy instrument on $CO_2$ emissions depends on whether or not the other policy instrument is already in place. The simulation results presented in this chapter indicate that in most countries the interaction effect is positive. This means that the $CO_2$ emission reduction in the electricity sector due to a policy instrument is enlarged by the presence of the other. Nevertheless, some countries show negative interaction. This interaction effect between EU ETS and RES-E deployment is further examined in chapter 6.

# Chapter 5

# Impact of RES-E deployment and $CO_2$ cap on EUA price

This chapter discusses the impact of RES-E deployment and EU ETS on $CO_2$ emissions in the electricity sector and the EUA price, starting from the *ETS-cap assumption*. According to the ETS-cap assumption, EU ETS is modeled as a $CO_2$ emission cap imposed on the electricity generators. This assumption implies that the electricity sector is responsible for all $CO_2$ emissions covered by EU ETS. Within this cap, RES-E deployment shifts $CO_2$ emissions within the modeled part of the electricity sector and therefore the EUA price is function of the amount of RES-E injections.

This chapter only deals with the RES scenario as the difference between the ETS-cap assumption and the ETS-price assumption is only reflected in this scenario.

This chapter first discusses the $CO_2$ abatement curves of the electricity sector in section 5.1. These curves provide a link between $CO_2$ abatement in the electricity sector and the EUA price. In section 5.2, the impact of EU ETS and RES-E deployment on the EUA price is examined followed by an estimation of the actual impact of EU ETS and RES-E deployment on both $CO_2$ emissions in the electricity sector and the EUA price. Finally, $CO_2$ displacement within the electricity sector operating under a $CO_2$ emission cap due to RES-E injections is discussed in section 5.3.

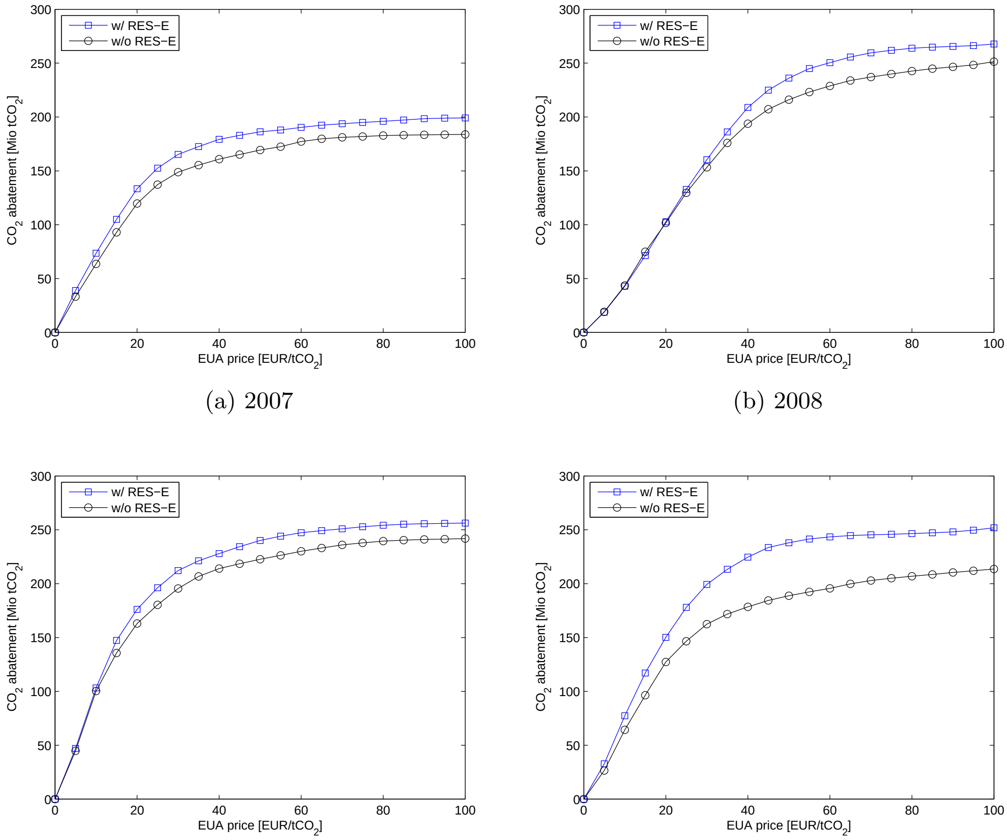
## 5.1 $CO_2$ abatement curve of the electricity sector

Figure 5.1 shows the $CO_2$ abatement curves for the electricity sector covered by the model for 2007, 2008, 2009 and 2010. Only short term operational aspects are taken into account and long term changes in the production plant portfolio are not considered. From an operational point of view, an EUA price causes $CO_2$ abatement by means of fuel switching, i.e. replacing $CO_2$ intensive generation by generation from less $CO_2$ intensive power plants which were initially not operating. For $CO_2$

prices up to 20 EUR/t$CO_2$, abatement curves are almost linear. At EUA prices above 60 EUR/t$CO_2$, abatement curves become almost flat as nearly all possible fuel switching has already occurred. The $CO_2$ abatement curves are similar for the different years.

The presence of RES-E deployment influences the $CO_2$ abatement curves. All $CO_2$ abatement curves demonstrate higher $CO_2$ abatement at the same EUA price when RES-E deployment is in place. This indicates the positive interaction regarding $CO_2$ emission reductions between EU ETS and RES-E deployment. This positive interaction effect is more explicit at higher EUA prices.

The abatement curves can be linked with the results presented in the previous chapter (see chapter 4). The $CO_2$ abatement attributable to EU ETS follows from the abatement curve at average historical EUA price[1].




(a) 2007

(b) 2008

(c) 2009

(d) 2010

FIGURE 5.1: $CO_2$ abatement curves of the electricity sector in MS12, with and without RES-E deployment.

[1] 0,79 EUR/t$CO_2$ in 2007, 22,06 EUR/t$CO_2$ in 2008, 13,15 EUR/t$CO_2$ in 2009 and 14,31 EUR/t$CO_2$ in 2010

The $CO_2$ abatement curves presented in this section are derived from the electricity generation model by simulating a whole year with different constant EUA prices imposed on the electricity sector. As such, the abatement curves are aggregated in space and in time. The abatement curve with RES-E deployment in place is determined as the difference in annual $CO_2$ emissions in the electricity sector between the RES scenario and the OBS scenario. The abatement curve without RES-E deployment in place is determined as the difference in annual $CO_2$ emissions in the electricity sector between the NOPOL scenario and the ETS scenario. A different way to obtain $CO_2$ abatement curves from the model is to impose different $CO_2$ emission caps to the electricity sector. This approach leads to slightly different abatement curves as a constant daily EUA price is not equivalent to an annual $CO_2$ emission cap. However, it is easier to implement the first approach in the model compared to the latter.

## 5.2 Impact of RES-E deployment under a $CO_2$ emission cap

RES-E deployment displaces $CO_2$ emissions within the EU ETS emission cap and reduces the demand for emission allowances. RES-E deployment hence influences at the same time $CO_2$ emissions in the electricity sector and the EUA price in all EU ETS sectors. This section first determines the maximum EUA price reduction due to RES-E deployment. Subsequently, this EUA price reduction is combined with the results from the previous chapter to estimate the actual impact of EU ETS and RES-E deployment on both $CO_2$ emissions in the electricity sector and the EUA price.

### 5.2.1 Impact of RES-E deployment on the EUA price

The maximum EUA price reduction occurs when RES-E deployment does not shift any $CO_2$ emissions to other ETS sectors, i.e. when the electricity sector operates under its own emission cap. In this case, $CO_2$ free RES-E injections can be compensated by higher emission from especially coal power plants. Without RES-E injections, a high EUA price is required to limit generation from coal power plants and stimulate generation from gas power plants.

In the OBS scenario, the electricity sector emitted 957 million $tCO_2$ in 2007, 906 million $tCO_2$ in 2008, 874 million $tCO_2$ in 2009 and 854 million $tCO_2$ in 2010. To limit emissions without RES-E injections to historical levels, the EUA price should be significantly higher. The EUA price increase is determined by imposing the historical annual $CO_2$ emissions as $CO_2$ emission cap to the ETS scenario. The annual emission cap is divided in weekly emission caps based on a combination of historical weekly $CO_2$ emissions and weekly electricity demand. From this analysis follows that in 2007, an average EUA price of 15,01 EUR/$tCO_2$ is needed while the historical EUA price at that time was only 0,79 EUR/$tCO_2$. In 2008 an increase in average EUA price from 22,06 EUR/$tCO_2$ to 67,56 EUR/$tCO_2$ is required and in

2010 an increase in average EUA price from 14,31 EUR/t$CO_2$ to 474,25 EUR/t$CO_2$ is needed. In 2009, historical $CO_2$ emissions can not be reached without RES-E injections. This is mathematically translated into an infinite EUA price required to reduce $CO_2$ emissions to historical levels in absence of RES-E deployment. All results are summarized in table 5.1.

These EUA price increases can be verified by the $CO_2$ abatement curves of the electricity sector. In 2008, the average historical EUA price was 22,06 EUR/t$CO_2$, corresponding to a $CO_2$ abatement of 118 million t$CO_2$ in absence of RES-E deployment (see figure 5.1b). Starting from the ETS-price assumption, RES-E deployment leads to another 116 million t$CO_2$ of abatement in the electricity sector, resulting in a total $CO_2$ abatement of 234 million t$CO_2$. The $CO_2$ abatement curve indicates that an EUA price of 65,29 EUR/t$CO_2$ is required for accomplishing this abatement. Note that according to table 5.1, an EUA price of 67,56 EUR/t$CO_2$ is needed to reach historical $CO_2$ emissions in the electricity sector in absence of RES-E deployment. The reason behind this difference is the way EU ETS is modeled. One way is to model EU ETS as a constant daily EUA price - applied for determining the $CO_2$ abatement curves - and another way is to cap weekly $CO_2$ emissions - applied for determining the EUA price increases presented in table 5.1. As both methods are not entirely equivalent, simulation results differ slightly. Analogously, the EUA price for 2007 can be determined from the $CO_2$ abatement curve, i.e. 17,45 EUR/t$CO_2$ compared to 15,01 EUR/t$CO_2$ according to table 5.1. In 2009 and 2010, EUA prices are located at the flat part of the abatement curve, making it difficult to use the $CO_2$ abatement curve to determine the EUA price accurately.

In summary, RES-E deployment reduces EUA price by maximum 15 EUR/t$CO_2$ in 2007, 46 EUR/t$CO_2$ in 2008 and 460 EUR/t$CO_2$ in 2010. In 2009, RES-E injections are needed to reach the historical $CO_2$ emission level.

| | | OBS scenario | RES scenario | |
|---|---|---|---|---|
| | | | ETS-price ass. | ETS-cap ass. |
| **2007** | | | | |
| $CO_2$ emissions | [Mio t$CO_2$] | 957 | 1057 | 957 |
| EUA price | [EUR/t$CO_2$] | 0,79 | 0,79 | 15,01 |
| **2008** | | | | |
| $CO_2$ emissions | [Mio t$CO_2$] | 906 | 1022 | 906 |
| EUA price | [EUR/t$CO_2$] | 22,06 | 22,06 | 67,56 |
| **2009** | | | | |
| $CO_2$ emissions | [Mio t$CO_2$] | 874 | 1017 | 874 |
| EUA price | [EUR/t$CO_2$] | 13,15 | 13,15 | infinite |
| **2010** | | | | |
| $CO_2$ emissions | [Mio t$CO_2$] | 854 | 983 | 854 |
| EUA price | [EUR/t$CO_2$] | 14,31 | 14,31 | 474,25 |

TABLE 5.1: Overview of annual $CO_2$ emissions and the average EUA price.

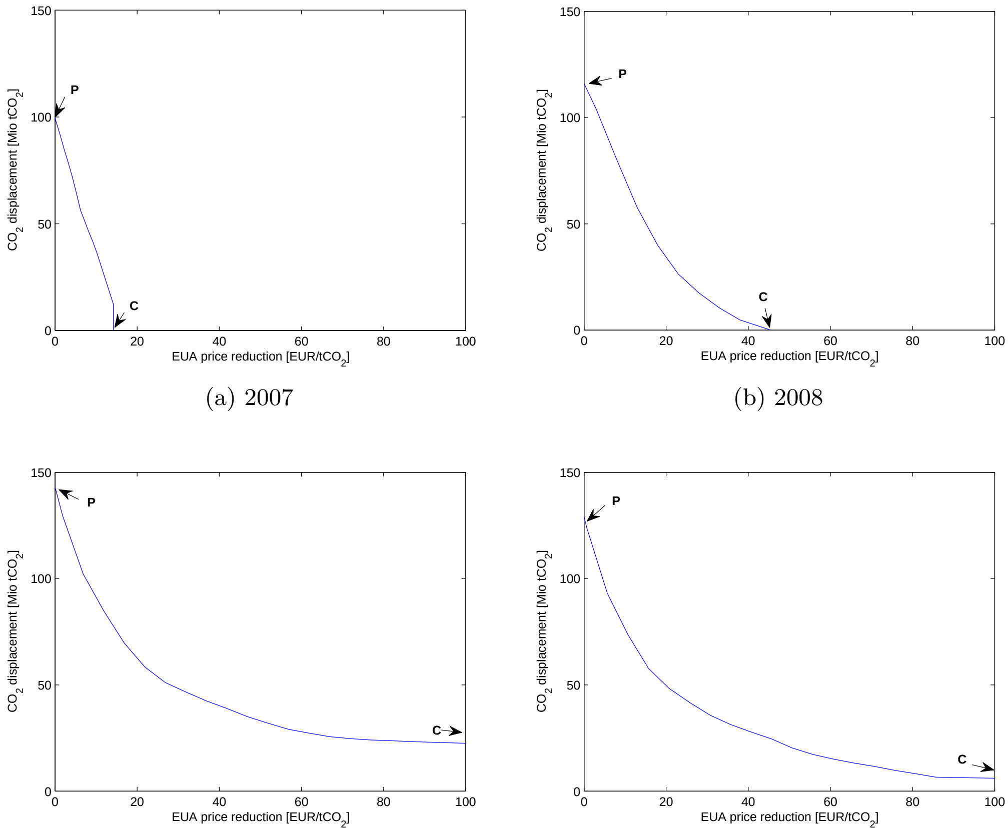
### 5.2.2 Correction for ETS-price assumption and ETS-cap assumption

So far, the RES scenario is considered consecutively under the ETS-price assumption in the previous chapter and the ETS-cap assumption in this chapter. Starting from the ETS-price assumption, historical EUA prices are imposed on the electricity generators in absence of RES-E deployment. In this case, the introduction of RES-E deployment does not change the EUA price but causes a displacement of $CO_2$ emissions from the electricity sector to other ETS sectors. In 2007, this $CO_2$ displacement is 100 million $tCO_2$, in 2008 116 million $tCO_2$, in 2009 143 million $tCO_2$ and in 2010 129 million $tCO_2$. Starting from the ETS-cap assumption, historical $CO_2$ emissions are imposed as $CO_2$ emission cap in the RES scenario. In this case, the introduction of RES-E deployment does not cause $CO_2$ abatement in the electricity sector but causes a reduction in EUA price of 15 EUR/$tCO_2$ in 2007, 46 EUR/$tCO_2$ in 2008 and 460 EUR/$tCO_2$ in 2010. In 2009, RES-E injections are needed to reach the historical $CO_2$ emission level.

In reality, RES-E deployment reduces the EUA price and displaces $CO_2$ emissions from the electricity sector to other ETS sectors at the same time. Figure 5.2 gives an overview of possible combinations of $CO_2$ displacement and EUA price reduction due to RES-E deployment. $CO_2$ displacement at zero EUA price reduction corresponds to the ETS-price assumption (see points P in figure 5.2) and EUA price reduction at zero $CO_2$ displacement corresponds to the ETS-cap assumption (see points C in figure 5.2). The curves between those extrema are determined by simulating the RES scenario with different constant EUA prices imposed on the electricity generators. The larger the amount of RES-E injections, the larger the range of possible EUA price reductions and $CO_2$ displacements. Note that $CO_2$ displacement only refers to $CO_2$ emissions shifted from the modeled part of the electricity sector to non-modeled ETS sectors. Emissions displaced within the modeled electricity sector are not included in the $CO_2$ displacement depicted on the y-axis.

Figure 5.2 is only valid at the historical $CO_2$ emission cap imposed by EU ETS on all ETS sectors. If this emission cap would change, the reference point with which the impact of RES-E deployment is compared would change as well and hence figure 5.2 is no longer valid.

The combination of figure 5.2 with the abatement curve of all ETS sectors not included in the model gives the actual impact of RES-E injections at historical $CO_2$ emission cap. This can be understood as follows: consider figure 5.2d, an EUA price reduction of 20 EUR/$tCO_2$ corresponds to a $CO_2$ displacement of 50 million $tCO_2$ from the modeled electricity sector to non-modeled ETS sectors. If this point represented the actual impact of RES-E deployment, it would mean that the non-modeled ETS sectors emit 50 million $tCO_2$ more due to an EUA price decline of 20 EUR/$tCO_2$. This reasoning is however only useful from a theoretical point of view as no accurate $CO_2$ abatement curve of all non-modeled sectors is available.




(a) 2007 (b) 2008

(c) 2009 (d) 2010

FIGURE 5.2: The range of impact of RES-E deployment on EUA price and $CO_2$ displacement from the modeled electricity sector to other ETS sectors, when introduced with EU ETS in place. 156 TWh RES-E injections in 2007, 176 TWh RES-E injections in 2008, 202 TWh RES-E injections in 2009 and 226 TWh RES-E injections in 2010.

## 5.3 $CO_2$ displacement within electricity sector due to RES-E deployment

Total $CO_2$ emissions in the electricity sector are capped and hence independent from RES-E injections. However, $CO_2$ emissions are displaced within the European electricity sector due to RES-E injections. This section discusses the displacement of $CO_2$ emissions when RES-E deployment is introduced in presence of a $CO_2$ emission cap. Note that the $CO_2$ displacement discussed in this section is not the same as the $CO_2$ displacement discussed in the previous section. This section deals with $CO_2$ displaced within the modeled electricity sector itself, whereas the previous section dealt with $CO_2$ displacement from the modeled electricity sector to non-modeled ETS sectors.

Figure 5.3 shows $CO_2$ displacement due to the introduction of RES-E injections for 2007, 2008 and 2010. 2009 is not considered as the historical $CO_2$ emission level can not be reached without RES-E injections. A positive displacement indicates that $CO_2$ emissions in that country increase due to the introduction of RES-E deployment. A negative displacement indicates that $CO_2$ emissions in that country decrease due to the introduction of RES-E injections. The annual sum of all $CO_2$ abatement equals zero.

This figure shows that the introduction of RES-E injections displace $CO_2$ emissions from Austria, Belgium, Italy, the Netherlands and Spain towards France and the United Kingdom. Almost no $CO_2$ emissions are displaced from or to Denmark and Ireland. RES-E injections shift $CO_2$ emissions from Portugal and Germany to other countries in 2007 and 2008, but attract $CO_2$ emissions to those countries in 2010. On average 5% of total $CO_2$ emissions are displaced if RES-E injections are introduced.

$CO_2$ displacement is the result of a change in generated electricity per country and a change in fuel share in each country. Both factors are successively discussed.

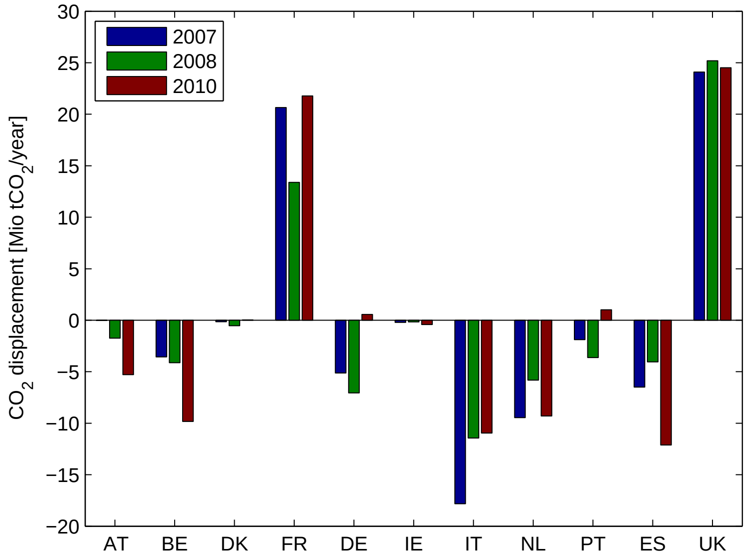



FIGURE 5.3: $CO_2$ displacement of $CO_2$ emissions due to the introduction of RES-E deployment in presence of a $CO_2$ emission cap. A positive $CO_2$ displacement indicates an increase in $CO_2$ emissions when RES-E deployment is introduced, a negative displacement indicates a decrease in $CO_2$ emissions when RES-E deployment is introduced. Luxembourg is not depicted as $CO_2$ displacement is negligible. 2009 is not considered as the historical $CO_2$ emission level of that year can not be reached without RES-E deployment.

Without RES-E deployment, RES-E injections have to be replaced by conventional generation from coal power plants, gas power plants and oil power plants. As $CO_2$ emissions are capped, RES-E injections are replaced as much as possible with gas power plants, which emit less $CO_2$ than coal and oil power plants. Gas and oil power plants also have to replace some of the original coal fired generation to compensate for the $CO_2$ emissions needed to replace RES-E injections. As a result, electricity generation will shift to countries with a large number of unused gas power plants when RES-E injections are removed.

Figure 5.4 shows respectively the amount of RES-E injections due to RES-E support schemes and the conventional generation that is avoided by these RES-E injections per country[2]. If avoided conventional generation is larger than RES-E injections, one can say that electricity generation is moved away from these countries when RES-E injections are introduced. This is the case for Belgium, Ireland, Italy, the Netherlands and Spain. This explains the decrease in $CO_2$ emissions in these countries when RES-E deployment is introduced (see figure 5.3). In Denmark, France, Germany and Portugal, RES-E injections are higher than avoided conventional generation, meaning generation is shifted towards these countries due to the introduction of RES-E injections. In France, avoided conventional generation is even negative, indicating that conventional generation is larger with RES-E injections in place than without. This explains the increase in $CO_2$ emission in France if RES-E injections are introduced. For Austria and the United Kingdom, it depends on the considered year whether generation is shifted towards or away from those countries, but on average one can say that these countries repel generation when RES-E injections are introduced.

Figure 5.5 shows that the countries whose generation increases in absence of RES-E injections, i.e. Austria, Belgium, Ireland, Italy, the Netherlands, Spain and the United Kingdom, have indeed a large capacity of unused dispatchable gas power plants which are used to compensate for the removed RES-E injections. This figure shows the annual generation from gas power plants in the OBS scenario, the RES-E injections which need to be replaced and the maximum possible generation from gas power plants. Gas fired cogeneration power plants are not taken into account as they are considered as non-dispatchable in the model. Germany and Portugal have just enough gas fired capacity to compensate for the loss of RES-E injections but not enough to replace original coal generation to keep $CO_2$ emission within the cap. France does not even have enough gas fired capacity to replace RES-E injections and Denmark has gas fired capacity in the form of dispatchable cogeneration plants but these power plants are not often used as their efficiency is lowered during the calibration of the model. Germany, Portugal, France and Denmark hence import more electricity - or reduce export - when RES-E injections are removed.

[2] Conventional generation in ETS scenario minus conventional generation in OBS scenario

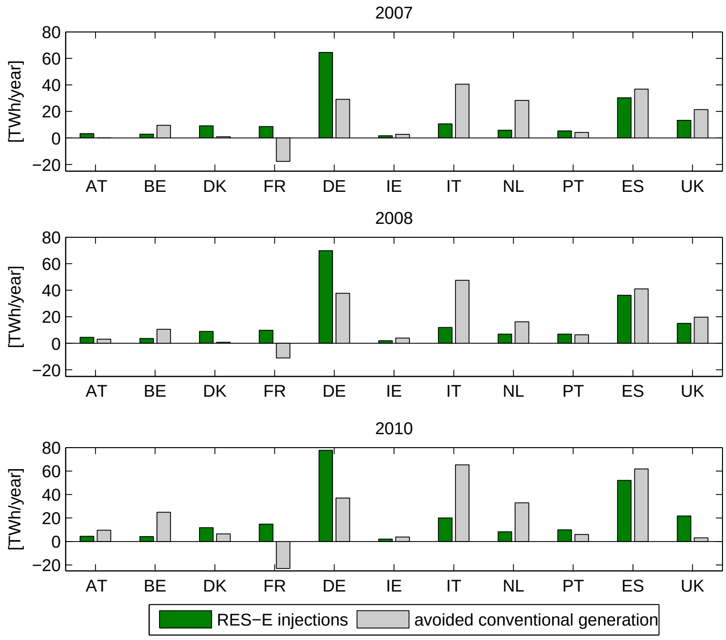



FIGURE 5.4: RES-E injections due to RES-E support schemes and the avoided conventional generation due to these RES-E injections.

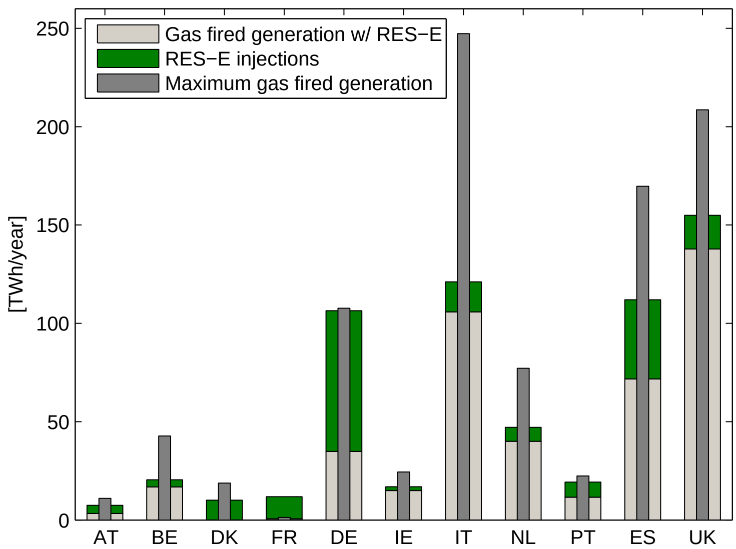



FIGURE 5.5: Availability of dispatchable gas power plants to replace RES-E injections (annual average values).

Besides a change in generated electricity per country, RES-E deployment also induces a change in fuel shares (see figure 5.6). Gas share decreases and coal share increases in every country when RES-E injections are introduced. The introduction of RES-E injections releases $CO_2$ emissions which are mainly occupied by coal power plants. Gas fired plants are less used as RES-E injections facilitate the electricity generators to reach the $CO_2$ emission cap. The $CO_2$ intensity of oil power plants lies between these of gas fired power plants and coal fired power plants. The change in oil share due to RES-E injections is therefore less unambiguous.

For the sake of completeness, one should note that RES-E deployment has also an influence on dual storage usage. In absence of RES-E injections, dual storage generation increases from 0,07 TWh to 0,13 TWh in 2007, from 0,18 TWh to 0,35 TWh in 2008 and from 0,07 TWh to 4,51 TWh in 2010. This implies an increase in total electricity generation of 0,08 TWh in 2007, 0,22 TWh in 2008 and 5,92 TWh in 2010. The reason for the increased usage of dual storage in absence of RES-E injections, is that expensive internal combustion units are needed to compensate for the lost RES-E generation. The use of internal combustion units at peak demand increases the price difference between off-peak and on-peak, making dual storage generation more often profitable. However, this effect can be neglected as annually generated electricity is about 2500 TWh.

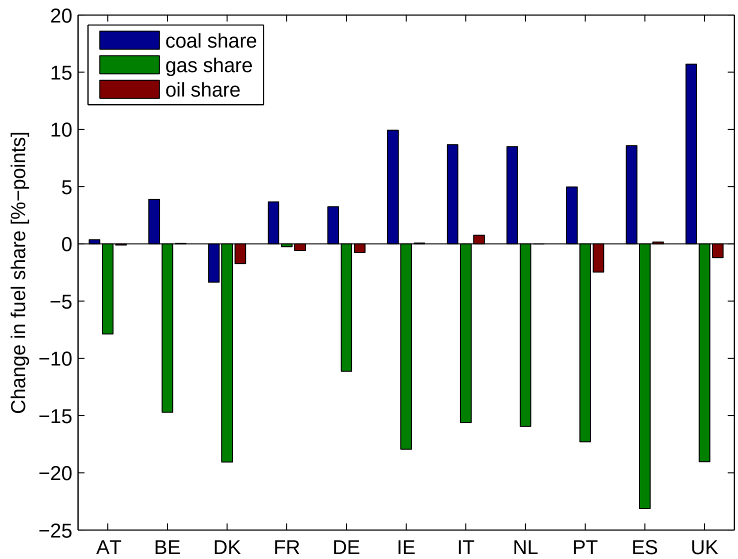



FIGURE 5.6: Changes in fuel shares due to the introduction of RES-E deployment. A positive change indicates an increase in fuel share due to the introduction of RES-E injections. A negative change indicates a decrease in fuel share due to the introduction of RES-E injections. 2007-2008-2010 average values.

Appendix B.1 and appendix B.2 give a detailed overview of $CO_2$ emissions and electricity generation under a $CO_2$ emission cap in the OBS scenario and the ETS scenario.

## 5.4 Summary

The aim of this master thesis is to quantify the impact of EU ETS and RES-E deployment on $CO_2$ emissions in the electricity sector and on the EUA price. EU ETS caps the $CO_2$ emissions from all ETS sectors, including the electricity sector, and puts a price on CO2 emissions. RES-E deployment displaces $CO_2$ emissions from the electricity sector to other ETS sectors and reduces at the same time the EUA price.

This chapter quantifies the impact of EU ETS and RES-E deployment on the EUA price, starting from the ETS-cap assumption. This assumption means that the electricity sector is subject to its own $CO_2$ emission cap and the introduction of RES-E deployment thus only causes a decline in EUA price. The ETS-cap assumption implies that the impact of RES-E deployment on the EUA price is overestimated as all the non-modeled ETS sectors are neglected.

To reach historical $CO_2$ emission levels in the electricity sector without RES-E injections, an EUA price of 15,01 EUR/t$CO_2$ would be needed in 2007 compared to a historical EUA price of 0,79 EUR/t$CO_2$ at that time. In 2008, an EUA price of 67,56 EUR/t$CO_2$ is needed compared to a historical price of 22,06 EUR/t$CO_2$ and in 2010, an EUA price of 474,25 EUR/t$CO_2$ is needed compared to a historical price of 14,31 EUR/t$CO_2$. In 2009, it is unfeasible to achieve historical $CO_2$ emissions without RES-E injections. RES-E deployment thus reduces the EUA price by maximum 15 EUR/t$CO_2$ in 2007, 46 EUR/t$CO_2$ in 2008 and 460 EUR/t$CO_2$ in 2010.

In reality, RES-E injection reduces EUA price and displaces $CO_2$ emissions from the electricity sector to other ETS sectors at the same time. Simulation results starting from the ETS-cap assumption and the ETS-price assumption define the range in which the actual impact of RES-E deployment is located at historical EU ETS emission cap. The ETS-cap assumption results in the maximum EUA price reduction due to RES-E deployment and the ETS-price assumption leads to the maximum $CO_2$ displacement. The combination of both extrema with the abatement curve of all ETS sectors not included in the model gives the actual impact of RES-E deployment on $CO_2$ emissions in the electricity sector and on the EUA price.

The introduction of RES-E deployment also causes $CO_2$ displacement within the modeled electricity sector. The analysis shows that RES-E injections displace $CO_2$ emissions from mainly Italy, the Netherlands and Spain towards France and the United Kingdom. This $CO_2$ displacement is caused by a change in generated electricity per country and a change in fuel share in each country. The introduction of RES-E injections shifts generation away from countries with a large reserve of gas power plants, i.e. Austria, Belgium, Ireland, Italy, the Netherlands, Spain and the United Kingdom, towards Denmark, France, Germany and Portugal. Besides a reallocation of generation per country, fuel shares change in each country. The introduction of RES-E injections leads to a decrease in gas share and an increase in coal share in each country. RES-E injections release $CO_2$ emission which are mainly occupied by coal fired generation. Gas shares decrease as RES-E injections facilitate the electricity generators to reach the $CO_2$ emission cap and therefore make gas generation less necessary.

# Chapter 6

# Interaction between EU ETS and RES-E support mechanisms

EU ETS and RES-E support mechanisms interact in multiple ways. This chapter focuses on the interaction between both policy instruments regarding the EUA price and regarding the impact on $CO_2$ emissions in the electricity sector.

Previously in this thesis, interaction between EU ETS and RES-E deployment was already mentioned a number of times. The results presented in chapter 4 demonstrate that the effect of one policy instrument on the $CO_2$ emissions in the electricity sector varies according to the presence of the other instrument. This interaction effect is referred to as *emission interaction*. Chapter 5 quantifies the reduction in EUA price due to RES-E deployment. This interaction effect is referred to as *price interaction*. Both phenomena are examples of interaction between EU ETS and RES-E deployment.

This chapter deals with the interaction effects mentioned earlier in this master thesis more thoroughly. Section 6.1 takes a step back and describes policy interaction between EU ETS and RES-E support mechanisms in general. Section 6.2 zooms in on the literature on price interaction. Subsequently, section 6.3 gives an overview of the emission interaction between EU ETS and RES-E deployment. In section 6.4, the mechanism behind this kind of interaction is examined and finally, in section 6.5 a parameter analysis is performed of the emission interaction effect.

The goal of this chapter is to quantify and examine the effect of interaction between EU ETS and RES-E deployment with regard to $CO_2$ emission reduction in the electricity sector and with regard to the EUA price. This chapter does not deal with the question what the policy setup should be for both policy instruments operating together.

## 6.1 Policy interaction between EU ETS and RES-E support mechanisms

Policy interaction exists when the operation of one policy instrument affects the operation or outcome of another policy instrument [6]. Boots et al. [6] classify interaction between EU ETS and RES-E deployment as *internal interaction*, i.e. interaction between two climate policy instruments, *vertical interaction*, i.e. interaction between a policy implemented on European level and a policy implemented on Member State level and *indirect interaction*, i.e. the target group directly affected by EU ETS overlaps with the target group indirectly affected by RES-E support schemes and vice versa. EU ETS targets large fossil fuel users, including electricity generators, while RES-E support schemes target renewable electricity generators. Conventional electricity generators and renewable electricity generators come together in the electricity market and therefore EU ETS and RES-E deployment interact indirectly.

EU ETS and RES-E deployment interact in multiple ways. Literature mentions interaction with regard to electricity prices, electricity generation from renewables and the EUA price (price interaction) [8]. Besides, EU ETS and RES-E deployment interact in another way, i.e. with regard to $CO_2$ emission reductions in the electricity sector (emission interaction). Emission interaction should be considered separately from price interaction.

## 6.2 Price interaction between EU ETS and RES-E support mechanisms

This section deals with policy interaction regarding the EUA price. In this respect, EU ETS and RES-E deployment interact as follows: EU ETS sets a $CO_2$ emission cap to all sectors operating under EU ETS, including the electricity sector, and puts a price on the emission of one ton $CO_2$, i.e. the EUA price. RES-E deployment reduces the demand for EUAs and therefore leads to a decline in EUA price.

The literature on price interaction considers - a part of - all ETS sectors and compares the EUA price in absence of RES-E deployment with the EUA price in presence of RES-E deployment.

Chapter 5 indicates a decline in EUA price due to RES-E deployment of 15 EUR/tCO2 in 2007, 46 EUR/tCO2 in 2008 and 460 EUR/tCO2 in 2010[1]. In reality, EUA price reduction due to RES-E deployment will probably be lower as only the electricity sector is considered with a stringent $CO_2$ emission cap imposed.

Hindsberger et al. [24] analysed the interaction between a $CO_2$ emission cap and a tradable green certificate (TGC) system. The scope of this analysis is the countries around the Baltic Sea[2]. Hindsberger et al. performed their analysis with the

[1] In 2009, RES-E injections were indispensable to reach the $CO_2$ emission cap, resulting in an infinite EUA price in absence of RES-E injections.

[2] i.e. Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Norway, Poland and Sweden.

Balmorel model, a long term investment model that determines electricity generation at minimum cost, supplemented with a model of the EUA market and the TGC market. The analysis covered the large perspective up to 2030 with a subdivision of each year into four quarters. The electricity sector is considered as a stand-alone sector with its own $CO_2$ emission cap. Hindsberger et al. concluded that for $CO_2$ emission reductions ranging from 0 % to 50 % of $CO_2$ emissions without cap and RES-E injections ranging from 0% to 25 % of aggregated electricity demand, RES-E deployment reduces the EUA price with 0 EUR/t$CO_2$ to 12 EUR/t$CO_2$.

Similar conclusions follow from an analysis by Unger and Ahlgren [39]. Unger and Ahlgren examined the interaction between a $CO_2$ emission cap and TGC quota. Their analysis covers the four Nordic countries[3] and focuses on the mid-term perspective, i.e. the period from 2005 to 2015. The analysis is performed with the MARKAL-NORDIC model, an optimizing linear-programming model that maximizes consumer and producer surplus. The MARKAL-NORDIC model leaves open the possibility of investments. In order to include the TEP market and TGC market, the MARKAL-NORDIC model was extended with a model of both markets. The TEP market is limited to the electricity sector and district-heating sector. Unger and Ahlgren concluded that for $CO_2$ emission reductions in the range of 10 % to 50 % of $CO_2$ emission without cap and RES-E injections ranging from 0 % to 30 % of aggregated electricity use, RES-E deployment reduces the EUA price with 0 EUR/t$CO_2$ to 20 EUR/t$CO_2$.

Rathmann [32] estimates the EUA price reduction due to RES-E deployment based on a theoretical analysis of the EUA market and the electricity market in Germany. His analysis is based on an estimated linear $CO_2$ abatement cost curve of all sectors within EU ETS and it takes only short term operational aspects into account. Rathmann concluded that the increase in RES-E injections of 29.4 TWh/year in the period from 2000 to 2007 due to support schemes resulted in an EUA price which is 27 % lower than it would be without additional RES-E injections.

## 6.3 Emission interaction between EU ETS and RES-E support mechanisms

The analysis described in this master thesis shows another way of interaction between EU ETS and RES-E deployment, i.e. emission interaction. The simulation results demonstrate that the $CO_2$ abatement in the electricity sector caused by an EUA price varies according to the presence of RES-E deployment. Analogously, $CO_2$ displacement from the electricity sector to other ETS sectors caused by RES-E deployment varies according to the presence of an EUA price.

The results presented in chapter 4 indicate positive emission interaction on a European scale and annual basis. The $CO_2$ displacement from the electricity sector to other ETS sectors due to RES-E deployment is on annual basis on average 7 % higher if EU

[3] i.e. Sweden, Norway, Denmark and Finland

ETS is in place compared to a scenario without EU ETS in place. Analogously, the impact of EU ETS on $CO_2$ abatement in the electricity sector is on annual basis on average 12 % higher if RES-E deployment is in place, compared to a scenario without RES-E deployment in place. However, if each country is considered separately, 34 cases indicate positive emission interaction and 10 negative emission interaction[4].

The emission interaction effect also becomes clear from the $CO_2$ abatement curves of the electricity sector, presented in chapter 5. The abatement caused by an EUA price is larger if RES-E deployment is in place. This effect becomes more pronounced at higher EUA prices. This implies a positive interaction effect.

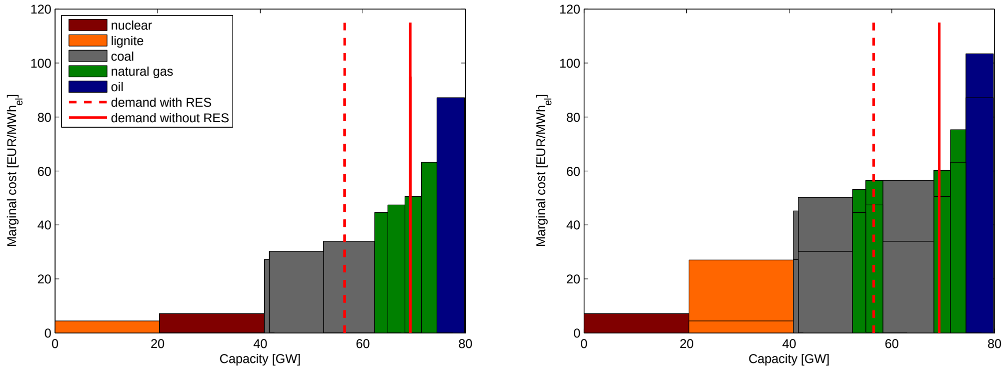
On a European scale and annual basis, the interaction effect can be considered as positive while on a national scale and annual basis, the analysis shows both positive and negative interaction effects. This raises the question which parameters determine the interaction effect to be positive or negative. To answer this question, an analysis of the interaction effect on hourly basis is required. This analysis is performed in the next section.

## 6.4 The mechanism behind emission interaction

The emission interaction effect is best explained by means of a stacking diagram. Figure 6.1 and figure 6.2 show the stacking diagrams for respectively an hour with positive emission interaction and an hour with negative emission interaction. These diagrams represent the actual merit order during one hour of the simulation. The left panels show the merit order without $CO_2$ emission cost and the right panels show the merit order including $CO_2$ emission cost. Each stacking diagram consists of a nuclear power plant type, a lignite fired power plant type, three types of coal fired power plants varying in capacity and efficiency, four types of gas fired power plants varying in capacity and efficiency and one type of oil fired power plants. Note that all power plants of a type are grouped and represented as one generation block in the merit order. Original electricity demand is reduced with generation from run-of-river plants, cogeneration plants, geothermal plants, waste fired power plants and single storage generation to obtain the demand depicted by the solid lines. Demand after correction for RES-E injections from solar energy, wind energy and bio-energy is displayed by the dashed lines. Marginal generation cost in the left panels only includes fuel cost. In the right panels, marginal generation cost consists of fuel cost (bottom part, equal to marginal generation cost of the left panel) and $CO_2$ emission cost (upper part). Note that, in absence of a $CO_2$ emission cost, the marginal generation cost of lignite fired power plants is lower than the marginal generation cost of nuclear power plants. This is due to a lower fuel cost for lignite compared to uranium. These fuel prices are, however, arbitrary set at a low price as these commodities are not traded on exchanges.

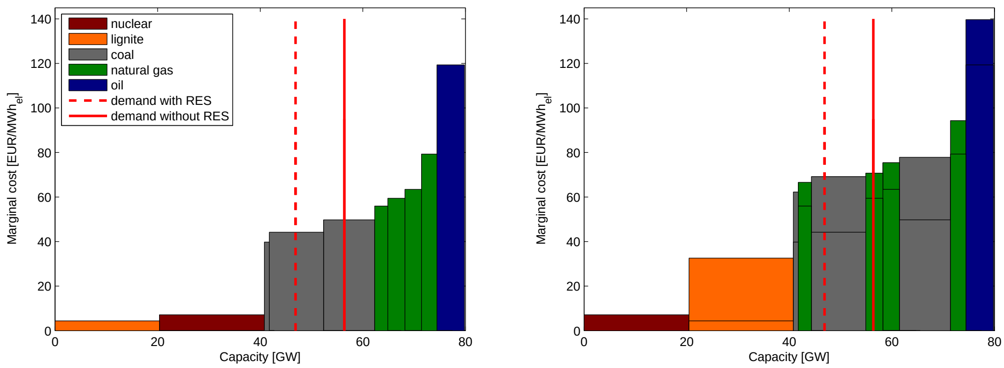
[4] 44 considered cases consisting of 11 countries times 4 years. Luxembourg is not considered as no $CO_2$ abatement occurs.

The stacking diagrams show how a $CO_2$ emission cost and RES-E injections influence $CO_2$ emissions in the electricity sector and interact with each other. The effect of RES-E deployment can be understood by comparing the solid demand line with the dashed demand line. RES-E injections lower the need for conventional generation and therefore generation of the power plants between the solid demand line and the dashed demand line is avoided by RES-E injections. However, the presence of a $CO_2$ emission cost affects the stacking order. In figure 6.1, RES-E injections avoid both coal fired generation and gas fired generation in absence of a $CO_2$ emission cost while in presence of a $CO_2$ emission cost mainly coal fired generation is avoided. The impact of RES-E deployment on $CO_2$ emissions is hence larger in presence of a $CO_2$ emission cost, resulting in positive emission interaction. In figure 6.2, RES-E




(a) Without $CO_2$ emission cost (b) With $CO_2$ emission cost

FIGURE 6.1: Merit order during an hour with positive emission interaction. Germany 2008, hour 565, positive emission interaction of 18 kt$CO_2$/hour.




(a) Without $CO_2$ emission cost (b) With $CO_2$ emission cost

FIGURE 6.2: Merit order during an hour with negative emission interaction. Germany 2008, hour 3752, negative emission interaction of 14 kt$CO_2$/hour.

injections avoid only coal fired generation in absence of a $CO_2$ emission cost while both coal fired generation and gas fired generation are avoided when a $CO_2$ emission cost is imposed on the electricity generators. Hence, the impact of RES-E injections is larger in absence of a $CO_2$ emission cost which implies negative emission interaction.

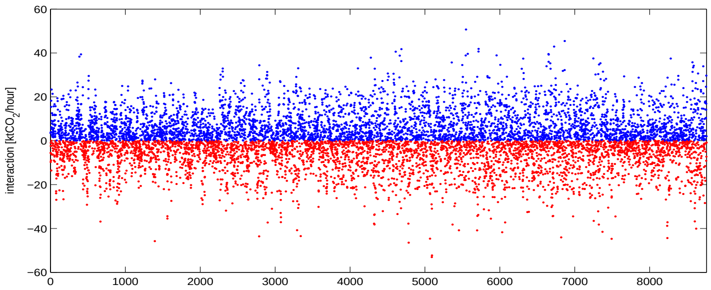
The effect of EU ETS on $CO_2$ emissions can be understood from a comparison between the left panel and the right panel from figure 6.1 and figure 6.2. A $CO_2$ emission cost moves coal generation blocks up in the merit order and gas generation blocks down. These changes in the merit order only result in $CO_2$ abatement when gas power plants are shifted from reserve to active use and coal power plants from active use to reserve. If generation blocks are shifted from active use to reserve and vice versa, fuel switching occurs. However, the presence of RES-E injections affects the boundary between active power plants and power plants kept as reserve. In figure 6.1, the introduction of a $CO_2$ emission cost without RES-E deployment does not result in $CO_2$ abatement as no fuel switching occurs, while, in the presence of RES-E deployment, a $CO_2$ emission cost leads to fuel switching of half a coal based generation block. The emission interaction effect is positive in this example. In figure 6.2, the introduction of a $CO_2$ emission cost without RES-E deployment in place leads to a fuel switch of about one and a half gas fired generation block. In presence of RES-E deployment, only one gas fired generation block is switched from reserve to active use. The emission interaction effect is thus negative.

Note that both reasonings, starting from the operation of RES-E deployment and starting from the operation of EU ETS, are identical.

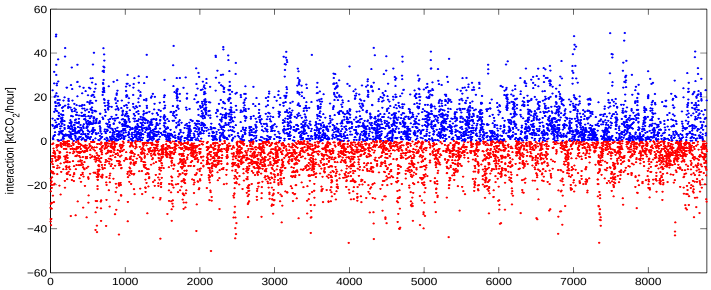
These examples illustrate that four parameters determine the emission interaction effect. The gas/coal price ratio and the EUA price determine the stacking order. Electricity demand and RES-E injections set the boundary between power plants in operation and power plants kept as reserve. A combination of these four parameters can lead to positive emission interaction or negative emission interaction. The interaction effect is thus not only function of parameters inherent to the considered policy instrument (RES-E injections and the EUA price), but also of exogenous parameters (electricity demand and fuel prices).

As the interaction effect is function of four parameters which vary over time, also the interaction effects itself varies over time. Both magnitude and sign of the emission interaction effect vary strongly. Figure 6.3 presents the hourly emission interaction effect for 2007, 2008, 2009 en 2010. No pattern in the variation of the interaction effect can be observed at this level of the analysis.

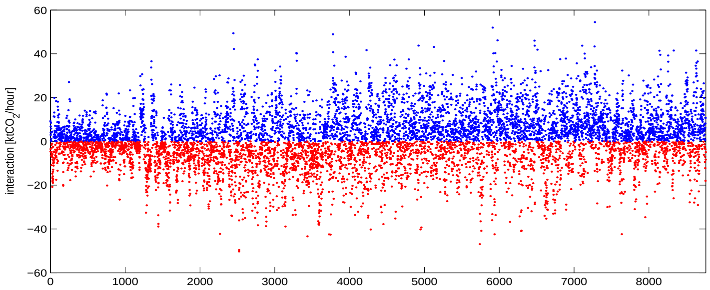
The hourly interaction effect can be obtained by comparing the hourly emission data from the different scenarios. No minimum downtime or start-up costs are implemented in the model and hence each hour can be considered separately. The hourly values in the different scenarios can be compared as hourly dual storage usage differ barely between the different scenarios. The deviation in hourly electricity generation between the different scenarios is maximum 0,009 % of total electricity demand during that hour.



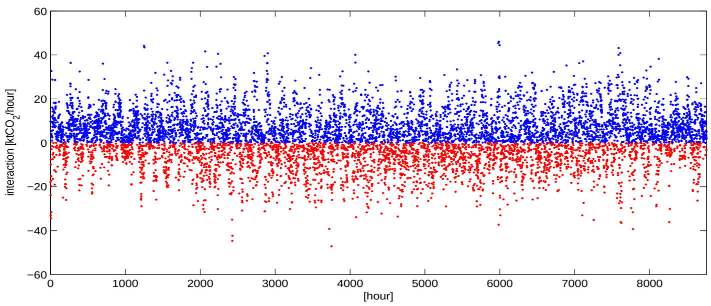

(a) 2007




(b) 2008




(c) 2009




(d) 2010

FIGURE 6.3: Hourly $CO_2$ emission interaction. Positive interaction is depicted in blue, negative interaction in red.

## 6.5 Parameter analysis of emission interaction

The emission interaction effect is function of the EUA price, the gas/coal price ratio, the amount of RES-E injections and the demand for electricity. As these four parameters vary over time, the interaction effect does as well. This section examines the sensitivity of the emission interaction effect to variations in the four parameters.

Throughout the period 2007-2010, the EUA price varied in the range from 0 EUR/t$CO_2$ to about 30 EUR/t$CO_2$, (see figure 2.3 on page 13). The gas/coal price ratio ranged from about 1 to about 3 (see figure 2.7 on page 15). Hourly electricity demand in MS12 varied from 190 GW to 396 GW during the period 2007-2010 with demand after single storage correction varying from 180 GW to 383 GW. Hourly RES-E injections ranged from 6 GW to 60 GW.

The parameter analysis considers one hour with average fuel prices and average generation from power plants whose output is set, i.e. nuclear power plants, lignite fired power plants, run-of-river power plants, waste based power plants, geothermal power plants and cogeneration power plants. Hourly emission interaction is determined for this hour for different combinations of EUA price, gas/coal price ratio, RES-E injections and electricity demand.

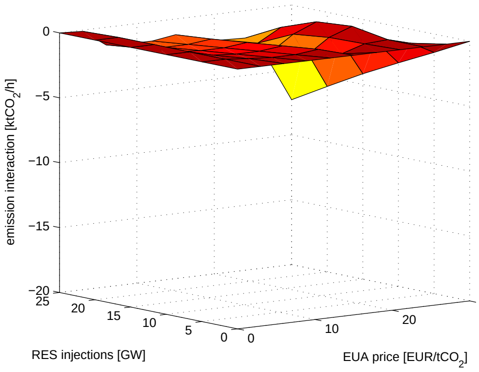
In a first subsection, the interaction effect is examined as a function of electricity demand, EUA price and RES-E injections at historical fuel prices. In a second subsection, the interaction effect is described as a function of gas/coal price ratio, EUA price and RES-E injections at historical electricity demand.

### 6.5.1 Emission interaction as a function of demand, EUA price and RES-E injections

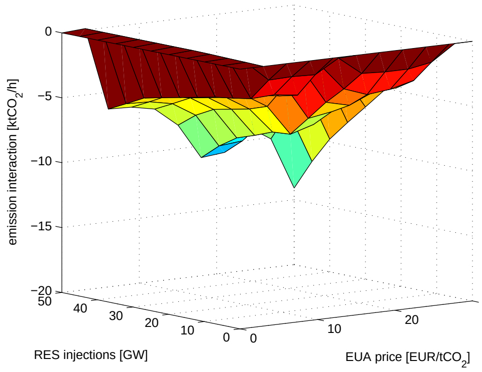
Figure 6.4 shows the emission interaction as function of RES-E injections and EUA price for different electricity demand levels at historical coal and gas prices in 2010.

No interaction effect occurs at zero EUA price or zero RES-E injections. In these cases, one policy instrument has no impact and hence no interaction can appear. At low electricity demand, the interaction effect is negative while at higher demand levels, the interaction effect becomes positive. At higher EUA price and more RES-E injections, absolute value of the interaction effect increases.

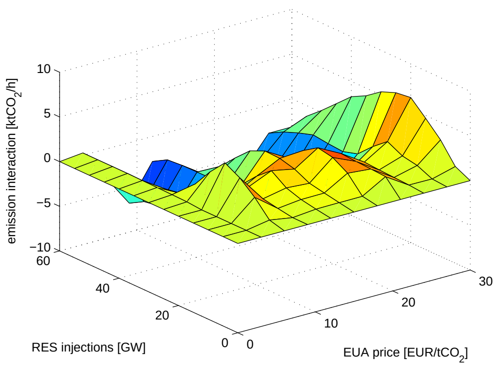
The trends indicated by figure 6.4 can be understood by reasoning on the stacking diagrams (see figures 6.1 and 6.2). Consider the introduction of RES-E deployment in respectively absence and presence of EU ETS. At low electricity demand and in a scenario without EU ETS and RES-E deployment (NOPOL scenario), electricity demand intersects the merit order in a coal fired generation block. The introduction of RES-E deployment in this case causes a reduction of coal fired generation. In a scenario with EU ETS but without RES-E deployment (ETS scenario), gas fired power plants are moved down in the merit order and the low electricity demand possibly intersects the merit order in a gas fired generation block. The introduction of RES-E deployment in this case results in a reduction of coal fired generation



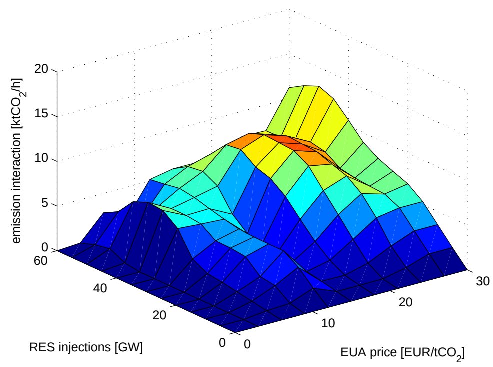

(a) demand = 225 GW



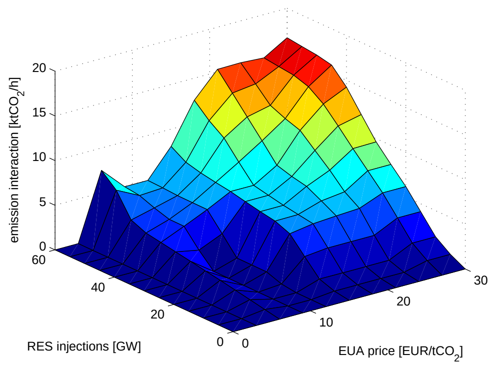

(b) demand = 250 GW



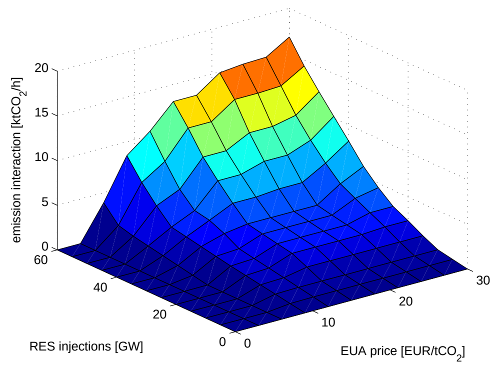

(c) demand = 275 GW




(d) demand = 300 GW




(e) demand = 325 GW




(f) demand = 350 GW

FIGURE 6.4: Emission interaction effect as function of RES-E injections and EUA price for different electricity demand levels and average 2010 historical fuel prices (a coal price of 10,36 EUR/MWh$_{prim}$ and a natural gas price of 17,83 EUR/MWh$_{prim}$).

and gas fired generation. As gas fired generation is less $CO_2$ intensive than coal fired generation, the interaction effect is negative. At higher electricity demand in the NOPOL scenario, electricity demand intersects the merit order in a gas fired generation block. The introduction of RES-E deployment in this case causes mainly a reduction in gas fired generation. In the ETS scenario, coal fired generation blocks are moved up in the merit order and hence RES-E deployment causes a reduction in both coal fired generation and gas fired generation. As coal fired generation is more $CO_2$ intensive than gas fired generation, the interaction effect is positive.

At an electricity demand of 225 GW, emission interaction is less negative than at an electricity demand of 250 GW. This is because in some countries, a very low electricity demand intersects the merit order in the nuclear generation block in absence of EU ETS. EU ETS switches the nuclear generation block with the lignite generation block (see figures 6.1 and 6.2) making the interaction effect positive at very low demand in countries with both nuclear capacity and lignite fired capacity. Therefore, the nett interaction effect in MS12 is less negative at a demand of 225 GW than at a demand of 250 GW.

At high electricity demand of 325 and 350 GW, the interaction effect at high EUA price and high RES-E injections is larger than the interaction effect at a demand of 300 GW. However, at moderate EUA prices and moderate RES-E injections, the interaction effect is about the same for a demand of 300 GW and for a demand of 325 GW or 350 GW. This indicates that the higher the electricity demand, the higher the interaction effect can be, but a high EUA price and high RES-E injections are needed to reach this large interaction effect.

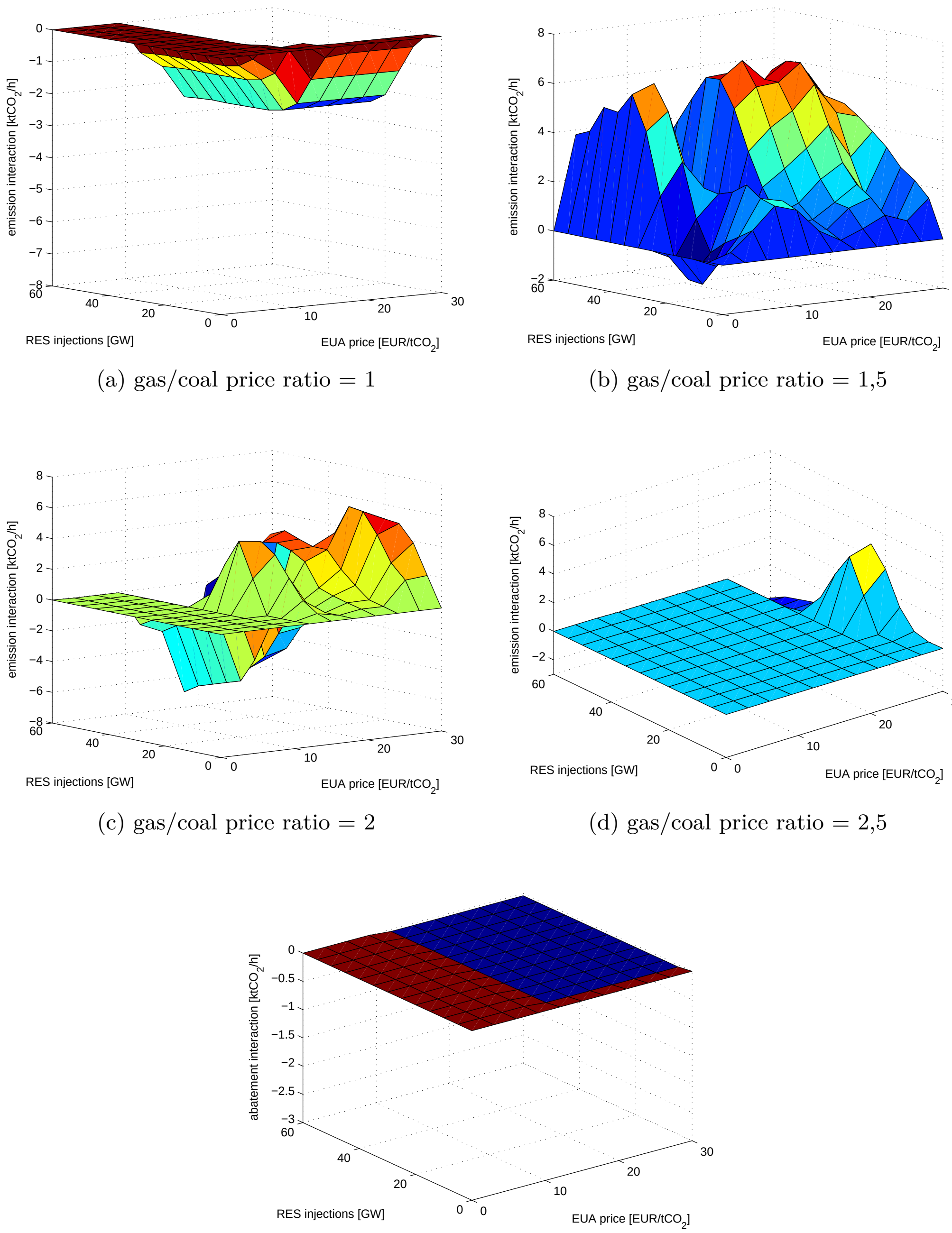
The same trends can be derived from an analysis with 2007, 2008 and 2009 historical fuel prices. Appendix C shows the emission interaction effect as function of electricity demand, EUA price and RES-E injections for these years.

In conclusion, one can say that at historical fuel prices the level of electricity demand determines whether the emission interaction effect is negative - at low electricity demand - or positive - at high electricity demand. Once the sign of the interaction effect is set by the electricity demand, the higher the EUA price and the more RES-E injections, the higher the absolute value of the emission interaction effect.

### 6.5.2 Emission interaction as a function of gas/coal price ratio, EUA price and RES-E injections

Figure 6.5 shows the interaction effect as function of RES-E injections and EUA price for different gas/coal price ratios and at historical electricity demand in 2010.

No interaction effect occurs at zero EUA price or zero RES-E injections. In these cases, one policy instrument has no impact and hence no interaction effect appears. At a gas/coal price ratio of 1, emission interaction is negative with a minimum interaction of -2,5 $ktCO_2/h$. Interaction becomes positive at a price ratio of 1,5 with a maximum of 6,7 $ktCO_2/h$. At a price ratio of 2, emission interaction can be both




(a) gas/coal price ratio = 1

(b) gas/coal price ratio = 1,5

(c) gas/coal price ratio = 2

(d) gas/coal price ratio = 2,5

(e) gas/coal price ratio = 3

FIGURE 6.5: Emission interaction effect as function of RES-E injections and EUA price for different gas/coal price ratios and average 2010 historical demand of 279 GW.

positive and negative, ranging from -7,0 kt$CO_2$/h to 5,8 kt$CO_2$/h. At higher price ratios, emission interaction becomes almost zero.

The trends showed in 6.5 can be explained by means of the merit order. The gas/coal price ratio determines the stacking order of gas fired power plants and coal fire power plants in the merit order. A merit order consists among others of three types of gas fired combined cycle power plants with an efficiency of 45 %, 48 % or 51 %, three types of coal fired power plants with an efficiency of 32 % , 36% or 40 % and one type of gas turbine units with an efficiency of 36 %. Consider a scenario without $CO_2$ emission cost. At a price ratio of 1, the marginal generation cost of the combined cycle power plants is lower than the marginal generation cost of the coal power plants because of the higher efficiency of the combined cycle power plants. In this case, the introduction of a $CO_2$ emission cost can only switch the gas turbine generation block with the high-efficiency coal generation block in the merit order. The effect of a $CO_2$ emission cost is thus limited and therefore the interaction effect between EU ETS and RES-E deployment is weak. A similar effect appears at high price ratios. In this case, the fuel part of the marginal generation cost of gas power plants is much higher than the fuel cost of coal power plants. A high $CO_2$ emission cost is needed to bridge the cost gap between both types of power plants. The effect of a $CO_2$ emission cost up to 30 EUR/t$CO_2$ is hence again limited and therefore the interaction effect is almost negligible.

At moderate gas/coal price ratios, the fuel cost gap between gas fired power plants and coal fired power plants can be easily bridged by a $CO_2$ emission cost. Consequently, EU ETS has a considerable impact on $CO_2$ emissions and emission interaction occurs.

In conclusion, one can say that the gas/coal price ratio determines the effect EU ETS can have. At a gas/coal price ratio of 1 and at high gas/coal price ratios as of 2,5, a $CO_2$ emission cost barely influences the $CO_2$ emissions in the electricity sector. At these price ratios, EU ETS is almost futile and hence no interaction with RES-E deployment occurs. For price ratios between 1 and 2,5, EU ETS can fully play its role and interaction with RES-E deployment occurs.

## 6.6 Summary

Policy interaction occurs when the outcome of one policy instrument is affected by the operation or outcome of another policy instrument [6]. EU ETS and RES-E support mechanisms interact in multiple ways. Both policy instruments affect each other concerning their impact on electricity prices, generation from renewable electricity sources and the EUA price. RES-E deployment reduces the EUA price and therefore interact with EU ETS. This interaction effect is referred to as *price interaction*.

The analysis described in this master thesis shows that EU ETS and RES-E deployment also interact with regard to $CO_2$ emission reductions in the electricity sector. The simulation results demonstrate that the $CO_2$ abatement in the electricity sector caused by an EUA price varies according to the presence of RES-E deployment.

Analogously, $CO_2$ displacement from the electricity sector to other ETS sectors caused by RES-E deployment varies according to the presence of an EUA price. This interaction effect is referred to as *emission interaction.* Emission interaction should be considered separately from price interaction.

Emission interaction between EU ETS and RES-E deployment can be understood as follows: RES-E injections avoid conventional generation from the most expensive power plants which should operate without RES-E injections. The EUA price influences the merit order and therefore the conventional generation avoided by RES-E injections. RES-E deployment and EU ETS hence interact. Emission interaction can also be comprehended starting from the operation of EU ETS. EU ETS causes $CO_2$ abatement in the electricity sector by pushing coal power plants from active use to reserve and pulling gas power plants in the opposite direction. The boundary between power plants in active use and power plants kept as reserve is, however, partly determined by the amount of RES-E injections. The more RES-E injections, the lower the electricity demand needed to be fulfilled by conventional generators and the fewer power plants in active use and vice versa. Thus, again it becomes clear that RES-E deployment and EU ETS interact.

The emission interaction effect is function of four parameters, i.e. the EUA price, the amount of RES-E injections, the electricity demand and the gas/coal price ratio. The electricity demand determines, together with the RES-E injections, the boundary between operating power plants and non-operating power plants. The gas/coal price ratio determines, together with the EUA price, the stacking order of gas fired and coal fired power plants in the merit order. As these four parameters fluctuate over time, emission interaction does as well.

A parameter analysis of the emission interaction effect indicates that, for the modeled electricity system and at historical fuel prices, at low electricity demand, emission interaction is negative and at higher electricity demand, emission interaction becomes positive. The interaction effect becomes more explicit - both in negative direction and in positive direction - at higher EUA price and more RES-E injections. For gas/coal price ratios close to 1 and higher than 2,5, emission interaction effect becomes negligible. At these price ratios, the fuel switching effect of EU ETS is so limited that EU ETS is futile and no interaction with RES-E deployment can occur.

# Chapter 7

# Conclusions

As of 2005, electricity generators in Europe operate under the EU ETS while, at the same time, receiving financial support for the deployment of renewable electricity sources like wind energy, solar energy and bio-energy. An imperative question is what the impact was of EU ETS and RES-E deployment on $CO_2$ emissions in the European electricity sector and on the EUA price. This question is answered in section 7.1. EU ETS and RES-E deployment interact regarding the EUA price and $CO_2$ emission reductions in the electricity sector. Section 7.2 summarizes the conclusion of this master thesis on these interaction effects. Finally, section 7.3 gives some recommendations for further research.

## 7.1 Impact of RES-E deployment and EU ETS

This master thesis quantifies the impact of EU ETS and RES-E deployment on $CO_2$ emissions in the Western and Southern European electricity sector and on the EUA price during the period 2007-2010. EU ETS caps the $CO_2$ emissions of all sectors operating under EU ETS, including the electricity sector. As such, EU ETS puts a price on the emission of a ton $CO_2$, i.e. the EUA price, and causes $CO_2$ abatement in all ETS sectors. Within the $CO_2$ emission cap set by EU ETS, RES-E deployment releases $CO_2$ emissions in the electricity sector and displaces part of these $CO_2$ emissions within the electricity sector itself and part from the electricity sector to other ETS sectors. As such, RES-E deployment lowers the demand for EUAs and thus reduces the EUA price. Note that only part of the European electricity sector is incorporated in the model.

The impact of RES-E deployment and EU ETS on respectively $CO_2$ emissions in the electricity sector and on the EUA price, is first considered separately after which they are combined to an estimation of the actual impact of RES-E deployment on both $CO_2$ emissions in the electricity sector and the EUA price. The maximum $CO_2$ displacement from the electricity sector to other ETS sectors due to RES-E deployment follows from an analysis starting from the *ETS-price assumption.* According to this assumption, an invariable EUA price is imposed on the electricity generators, independent from the amount of RES-E injections. This implies that the electricity sector is responsible for only a tiny part of all $CO_2$ emission covered by EU ETS. The conclusions based on the ETS-price assumption are discussed in section 7.1.1. The maximum decline in EUA price due to RES-E deployment follows from an analysis starting from the *ETS-cap assumption*. According to this assumption, the electricity sector is subject to its own $CO_2$ emission cap. This implies that $CO_2$ emissions in the electricity sector are capped but that the EUA price depends on the amount of RES-E injections. The conclusions based on the ETS-cap assumption are discussed in section 7.1.2. In section 7.1.3, the impact on $CO_2$ emissions in the electricity sector is combined with the impact on the EUA price.

### 7.1.1 Impact on $CO_2$ emissions

In 2007, 106 million $tCO_2$ is not emitted by electricity generators in Western and Southern Europe due to RES-E deployment and EU ETS - in the form of an invariable EUA price. This equates to 11 % of historical $CO_2$ emissions. The EUA price is almost negligible in 2007 but as of 2008, EUA price plays a more significant role resulting in higher $CO_2$ emission reductions in the electricity sector. In 2008, the reduction in $CO_2$ emissions is 234 million $tCO_2$ or 26 % of historical $CO_2$ emissions. In 2009, $CO_2$ emissions are reduced with 265 million $tCO_2$ or 30 % of historical $CO_2$ emissions. Finally, 221 million $tCO_2$ or 26 % of historical $CO_2$ emissions is not emitted in 2010 due to EU ETS and RES-E deployment.

Due to the low EUA price in 2007, only 6 % of $CO_2$ emission reductions in the electricity sector is attributable to EU ETS and 94 % to RES-E deployment. In 2008, 2009 and 2010, EU ETS and RES-E deployment contribute more or less equally to $CO_2$ emission reductions in the electricity sector. In 2008, 51 % of the emission reductions is attributable to EU ETS and 49 % to RES-E deployment. In 2009, 48 % of the emission reductions is attributable to EU ETS and 52 % to RES-E deployment. In 2010, 46 % of the emission reductions is attributable to EU ETS and 54 % to RES-E deployment. The relative impact of RES-E deployment increases from 2008 to 2010 due to the combination of increasing RES-E injections and a stable EUA price.

The impact of an EUA price and RES-E deployment on national $CO_2$ emissions in the electricity sector consists of a combination of two effects. First, the introduction of an EUA price and RES-E injections change the generated electricity per country. Second, the $CO_2$ intensity of electricity generation in each country changes as well. The introduction of an EUA price moves generation away from France and Germany towards almost all neighboring countries, i.e. the Benelux, Italy, Spain, Ireland and the United Kingdom. The introduction of RES-E injections shifts generation from Italy, the Benelux and the United Kingdom towards Austria, Denmark and Germany. The introduction of an EUA price and RES-E injections moves generation from France and to a lesser extent the United Kingdom and the Netherlands towards all other countries. Besides a reallocation of generated electricity per country, $CO_2$ intensity of electricity generation decreases in each country due to the EUA price and RES-E injections. On average, $CO_2$ intensity decreases with 77 $tCO_2$/GWh. Denmark and Germany show the largest decline in $CO_2$ intensity, mainly due to large amount of RES-E injections. Also in Ireland, Portugal, Spain and the United Kingdom, $CO_2$ intensity declines more than average. Austria, Belgium, France, Italy and the Netherlands face a smaller than average decline in $CO_2$ intensity. The combination of the two effects, i.e. reallocation of generation per country and decline in $CO_2$ intensity of electricity generation in each country, leads to a $CO_2$ emission reduction per country in the electricity sector due to an EUA price and RES-E deployment. In absolute terms, Germany, the United Kingdom, Spain and France show the largest $CO_2$ emission reductions.

One can divide all countries in the analysis in four groups based on the relative impact of EU ETS and RES-E deployment. In France and the United Kingdom, EU ETS has the main impact while in Spain, Portugal and Denmark, RES-E injections have the main impact. In Austria, Germany and Ireland, both policy instruments contribute about equally to $CO_2$ emission reductions. Belgium, the Netherlands and Italy show a negative EU ETS contribution, meaning that the introduction of an EUA price increases $CO_2$ emissions in these countries. This effect is due to a large fall in electricity import from France when an EUA price is introduced.

### 7.1.2 Impact on the EUA price

If EU ETS is implemented as a $CO_2$ emission cap imposed on the electricity sector, the introduction of RES-E injections result in an EUA price reduction. If the $CO_2$ emission cap is set at historical $CO_2$ emission levels in the electricity sector, the EUA price will increase considerably in absence of RES-E deployment. In 2007, an EUA price of 15 EUR/$tCO_2$ is needed to limit $CO_2$ emissions to the historical emission level in absence of RES-E injections, compared to a historical EUA price of 0,8 EUR/$tCO_2$. In 2008, an EUA price of 68 EUR/$tCO_2$ is needed compared to a historical price of 22 EUR/$tCO_2$ and in 2010, an EUA price of 474 EUR/$tCO_2$ is necessary coming from a historical price of 14 EUR/$tCO_2$. In 2009, it is unfeasible to limit $CO_2$ emissions to the historical level without RES-E injections. Thus, one can conclude that the maximal EUA price reduction due to RES-E deployment is 15 EUR/$tCO_2$ in 2007, 46 EUR/$tCO_2$ in 2008 and 460 EUR/$tCO_2$ in 2010.

The introduction of RES-E deployment in the electricity sector with capped $CO_2$ emission does not only result in a decline in EUA price but also in a displacement of $CO_2$ emissions within the electricity sector. The introduction of RES-E deployment displaces $CO_2$ emissions from Austria, Belgium, Italy, the Netherlands and Spain to France and the United Kingdom. Almost no $CO_2$ emissions are displaced from or to Denmark and Ireland. RES-E deployment shifts $CO_2$ emissions from Portugal and Germany to other countries in 2007 and 2008, but attract $CO_2$ emissions to these countries in 2010. On average 5 % of total $CO_2$ emissions are displaced due to the introduction of RES-E injections.

$CO_2$ displacement within the electricity sector results from a combination of change in electricity generation per country and a change in fuel shares in each country.

The introduction of RES-E injections moves generation away from Austria, Belgium, Ireland, Italy, the Netherlands, Spain and the United Kingdom. All these countries have a large capacity of dispatchable gas power plants which are frequently used in absence of RES-E injections. The $CO_2$ emissions released by RES-E injections, are filled in by coal power plants in Denmark, France, Germany and Portugal. In all countries, the introduction of RES-E deployment results in an increase in coal share and a decline in gas share.

### 7.1.3 Impact on $CO_2$ emissions and EUA price

So far, the impact of RES-E injections on $CO_2$ emissions in the electricity is expressed either as $CO_2$ displacement from the electricity sector to other ETS sectors or as EUA price decline. These two extrema determine the range in which the actual impact of RES-E injections on both $CO_2$ displacement and EUA price is located.

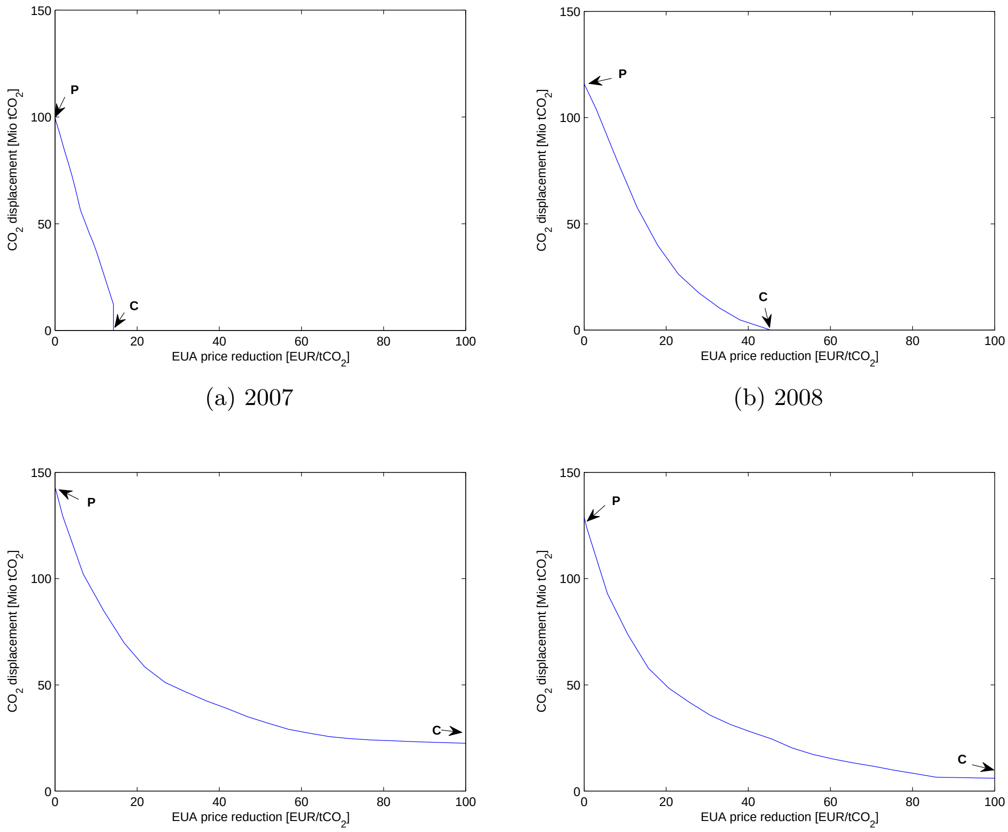
Figure 7.1 gives an overview of possible combinations of $CO_2$ displacement and EUA price reduction due to the introduction of RES-E deployment in presence of EU ETS. $CO_2$ displacement at zero EUA price reduction corresponds to the ETS-price assumption (see points P in figure 7.1) and EUA price reduction at zero $CO_2$ displacement corresponds to the ETS-cap assumption (see points C in figure 7.1).

The combination of figure 7.1 with the abatement curve of all ETS sectors not included in the model gives the actual impact of RES-E injections on the EUA price and $CO_2$ emissions in the electricity sector. This can be understood as follows: consider figure 7.1d, an EUA price reduction of 20 EUR/t$CO_2$ corresponds to a $CO_2$ displacement of 50 million t$CO_2$ from the modeled electricity sector to non-modeled ETS sectors. If this point represented the actual impact of RES-E deployment, it would mean that the non-modeled ETS sectors emit 50 million t$CO_2$ more due to an EUA price decline of 20 EUR/t$CO_2$.

Figure 7.1 is only valid at the historical $CO_2$ emission cap imposed by EU ETS on all ETS sectors. If this emission cap would change, the reference point with which the impact of RES-E deployment is compared would change as well and hence figure 7.1 is no longer valid.

## 7.2 Interaction between EU ETS and RES-E deployment regarding $CO_2$ emissions

Policy interaction exists when the operation of one policy instrument affects the operation or outcome of another policy instrument [6]. EU ETS and RES-E deployment interact in multiple ways. Literature mentions interaction with regard to electricity prices, electricity generation from renewables and the EUA price. This last type of interaction is referred to in this master thesis as *price interaction*, meaning that RES-E deployment reduces the EUA price.




(a) 2007

(b) 2008

(c) 2009

(d) 2010

FIGURE 7.1: The range of impact of RES-E deployment on EUA price and $CO_2$ displacement from the modeled electricity sector to other ETS sectors when introduced with EU ETS in place.

The analysis described in this master thesis shows that EU ETS and RES-E deployment also interact with regard to $CO_2$ emission reductions in the electricity sector. The simulation results demonstrate that the $CO_2$ abatement in the electricity sector caused by an EUA price varies according to the presence of RES-E deployment. Analogously, $CO_2$ displacement from the electricity sector to other ETS sectors caused by RES-E deployment varies according to the presence of an EUA price. This interaction effect is referred to as *emission interaction.* Emission interaction should be considered separately from price interaction.

The price interaction effect is already discussed in section 7.1.2. To repeat, the maximal EUA price reduction due to RES-E deployment is 15 EUR/$tCO_2$ in 2007, 45 EUR/$tCO_2$ in 2008 and 460 EUR/$tCO_2$ in 2010. These figures are the maximum EUA price decline as only the electricity sector is considered under a stringent $CO_2$ emission cap. The price interaction effect is studied starting from the ETS-cap assumption

On a European scale, the annual emission interaction effect in the electricity sector is positive, meaning that $CO_2$ displacement to other ETS sectors caused by RES-E deployment is larger when an EUA price is imposed on the electricity sector. The interaction effect is however limited, increasing the $CO_2$ displacement attributable to RES-E deployment with on average 7 %. Analogously, the $CO_2$ abatement due to an EUA price is on average 12 % higher if RES-E deployment is in place. On a national scale and annual basis, emission interaction is positive for most countries. However, some countries show negative emission interaction between RES-E deployment and EU ETS, meaning that $CO_2$ displacement due to RES-E deployment decreases when an EUA price is in place. The emission interaction effect is studies starting from the ETS-price assumption.

The mechanism behind the emission interaction effect can be understood as follows: RES-E injections avoid generation from the most expensive conventional power plants which should operate in absence of RES-E injections. The EUA price influences the merit order and therefore the conventional generation avoided by RES-E injections. RES-E deployment and EU ETS hence interact. Emission interaction can also be comprehended starting from the operation of EU ETS. EU ETS causes $CO_2$ abatement in the electricity sector by pushing coal power plants from active use to reserve and pulling gas power plants in the opposite direction. The boundary between power plants in active use and power plants kept as reserve is however partly determined by the amount of RES-E injections. The more RES-E injections, the lower the electricity demand needing to be fulfilled by conventional generators and the fewer power plants in active use. Thus, it becomes again clear that RES-E deployment and EU ETS interact. The emission interaction effect is function of four parameters, i.e. the EUA price, the amount of RES-E injections, the electricity demand and the gas/coal price ratio. As these four parameters fluctuate over time, emission interaction does as well.

A parameter analysis of the emission interaction effect indicates that, at historical fuel prices, a low electricity demand results in negative emission interaction and a higher electricity demand in positive emission interaction. The interaction effect becomes more explicit - both in negative direction and in positive direction - at a higher EUA price and more RES-E injections. The effect of EU ETS is directly determined by the gas/coal price ratio. At price ratios close to 1 and higher than 2,5, emission interaction effect becomes negligible as the fuel switching effect of EU ETS is so limited that EU ETS is futile and no interaction with RES-E deployment can occur.

## 7.3 Recommendations for further research

A first recommendation for further research concerns the electricity generation simulation model. In the current status of the model, power plants are grouped in 21 different types of power plants. An representation of the power plant portfolio on power plant level will further refine the simulation results. Besides, power plant dynamics are neglected in the current model. The implementation of system dynamics will also refine the simulation results.

A second recommendation for further research concerns the representation of the non-modeled EU ETS sectors in the analysis. In this thesis, the impact of RES-E injections on the EUA price is determined as an estimation between two extreme scenarios regarding the position of the electricity sector within EU ETS. Another approach could be to extend the model with the $CO_2$ abatement curve of the ETS sectors not included in the current model. Based on this extended model, the decline in EUA price due to RES-E injections could be estimated more accurately. The difficulty of this approach lies in the determination of an accurate $CO_2$ abatement curve of all ETS sectors excluding the electricity sector.

A last recommendation for further research addresses the impact of EU ETS and RES-E deployment on electricity prices. It is worthwhile to study the impact of EU ETS and RES-E deployment on electricity prices in a study similar to the one presented in this thesis. This study should focus on the impact of both policy instruments on wholesale electricity prices and the cost for society of both policy instruments.

# Appendices

# Appendix A

# Simulation results based on the ETS-price assumption

The results presented in this appendix follow from simulations based on the *ETS-price assumption*, meaning that EU ETS is modeled as an exogenous and invariable EUA price imposed on the electricity generators.

## A.1 $CO_2$ emissions in the electricity sector

Emission data are displayed for MS12 and each country, for each year from 2007 to 2010 and for each scenario.

| [Mio $tCO_2$] | 2007 | | 2008 | | 2009 | | 2010 | |
|---|---|---|---|---|---|---|---|---|
| | ETS | No ETS | ETS | No ETS | ETS | No ETS | ETS | No ETS |
| **MS12** | | | | | | | | |
| RES-E | 957 | 964 | 906 | 1.027 | 874 | 1.006 | 854 | 966 |
| No RES-E | 1.057 | 1.063 | 1.022 | 1.140 | 1.017 | 1.139 | 983 | 1.075 |
| **AT** | | | | | | | | |
| RES-E | 14,2 | 14,2 | 14,2 | 14,6 | 15,7 | 16,0 | 14,0 | 14,3 |
| No RES-E | 14,3 | 14,3 | 14,5 | 14,7 | 16,0 | 16,2 | 14,2 | 14,4 |
| **BE** | | | | | | | | |
| RES-E | 17,7 | 17,7 | 16,6 | 15,6 | 17,1 | 15,7 | 17,6 | 16,7 |
| No RES-E | 20,4 | 20,4 | 19,4 | 18,6 | 20,7 | 19,5 | 21,9 | 21,3 |
| **DK** | | | | | | | | |
| RES-E | 24,8 | 25,3 | 22,7 | 22,8 | 23,9 | 24,2 | 26,1 | 26,8 |
| No RES-E | 36,5 | 36,9 | 23,0 | 23,2 | 24,6 | 24,6 | 28,1 | 28,1 |
| **FR** | | | | | | | | |
| RES-E | 37,7 | 39,3 | 34,7 | 60,8 | 37,0 | 59,6 | 40,5 | 65,4 |
| No RES-E | 43,6 | 44,7 | 42,2 | 73,1 | 53,0 | 78,4 | 49,3 | 69,8 |

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| [Mio $tCO_2$] | 2007 | | 2008 | | 2009 | | 2010 | |
|---|---|---|---|---|---|---|---|---|
| | ETS | No ETS | ETS | No ETS | ETS | No ETS | ETS | No ETS |
| **DE** | | | | | | | | |
| RES-E | 321,4 | 322,9 | 300,1 | 338,1 | 289,6 | 327,0 | 289,5 | 316,2 |
| No RES-E | 352,4 | 354,4 | 346,1 | 387,8 | 345,1 | 376,7 | 323,3 | 338,0 |
| **IE** | | | | | | | | |
| RES-E | 14,7 | 14,8 | 14,5 | 15,9 | 13,7 | 14,5 | 13,2 | 13,6 |
| No RES-E | 15,6 | 15,7 | 15,4 | 16,7 | 14,8 | 15,4 | 14,2 | 14,4 |
| **IT** | | | | | | | | |
| RES-E | 141,1 | 140,6 | 136,3 | 133,1 | 137,7 | 136,1 | 134,0 | 129,4 |
| No RES-E | 149,6 | 149,1 | 147,3 | 141,1 | 150,1 | 147,8 | 152,5 | 148,7 |
| **LU** | | | | | | | | |
| RES-E | 1,1 | 1,1 | 0,9 | 0,9 | 0,9 | 0,9 | 1,1 | 1,1 |
| No RES-E | 1,1 | 1,1 | 0,9 | 0,9 | 0,9 | 0,9 | 1,1 | 1,1 |
| **NL** | | | | | | | | |
| RES-E | 52,8 | 53,0 | 51,1 | 51,2 | 49,7 | 48,9 | 49,0 | 47,8 |
| No RES-E | 62,2 | 62,3 | 59,3 | 58,1 | 56,8 | 57,0 | 58,5 | 58,3 |
| **PT** | | | | | | | | |
| RES-E | 20,2 | 20,4 | 20,0 | 21,8 | 17,6 | 21,3 | 17,6 | 20,5 |
| No RES-E | 22,9 | 23,0 | 24,6 | 25,3 | 22,7 | 25,1 | 22,5 | 24,6 |
| **ES** | | | | | | | | |
| RES-E | 117,9 | 118,5 | 105,9 | 115,1 | 92,6 | 108,0 | 77,4 | 84,9 |
| No RES-E | 134,2 | 134,8 | 124,6 | 131,7 | 116,4 | 129,3 | 102,3 | 108,4 |
| **UK** | | | | | | | | |
| RES-E | 193,6 | 196,3 | 189,4 | 236,7 | 178,1 | 233,6 | 174,6 | 229,2 |
| No RES-E | 204,3 | 206,0 | 204,2 | 248,6 | 195,8 | 248,6 | 194,5 | 247,5 |

TABLE A.1: Simulated $CO_2$ emissions in the electricity sector.

## A.2 $CO_2$ abatement in the electricity sector

$CO_2$ abatement data are displayed for MS12 and each country, for each year from 2007 to 2010 and for each scenario. Relative $CO_2$ abatement is expressed as percentage of $CO_2$ emissions in the OBS scenario.

| | $CO_2$ abatement | | Impact ETS [Mio $tCO_2$] | | Impact RES-E [Mio $tCO_2$] | |
|---|---|---|---|---|---|---|
| | [Mio $tCO_2$] | [%] | w/o RES-E | w/ RES-E | w/o ETS | w/ ETS |
| **MS12** | | | | | | |
| 2007 | 106 | 11 | 6 | 7 | 99 | 100 |
| 2008 | 234 | 26 | 118 | 121 | 113 | 116 |
| 2009 | 265 | 30 | 122 | 132 | 133 | 143 |
| 2010 | 221 | 26 | 92 | 112 | 109 | 129 |
| **AT** | | | | | | |
| 2007 | 0,1 | 1 | 0 | 0 | 0,1 | 0,1 |
| 2008 | 0,5 | 4 | 0,2 | 0,4 | 0,1 | 0,3 |
| 2009 | 0,5 | 3 | 0,2 | 0,3 | 0,2 | 0,3 |
| 2010 | 0,4 | 3 | 0,2 | 0,3 | 0,1 | 0,2 |
| **BE** | | | | | | |
| 2007 | 2,7 | 15 | 0 | 0 | 2,7 | 2,7 |
| 2008 | 2,0 | 12 | -0,8 | -1,0 | 3,0 | 2,8 |
| 2009 | 2,4 | 14 | -1,2 | -1,4 | 3,8 | 3,6 |
| 2010 | 3,7 | 21 | -0,6 | -0,9 | 4,6 | 4,3 |
| **DK** | | | | | | |
| 2007 | 12,1 | 49 | 0,4 | 0,5 | 11,6 | 11,7 |
| 2008 | 0,5 | 2 | 0,2 | 0,1 | 0,4 | 0,3 |
| 2009 | 0,7 | 3 | 0,0 | 0,3 | 0,4 | 0,7 |
| 2010 | 2,0 | 8 | 0,0 | 0,7 | 1,3 | 2,0 |
| **FR** | | | | | | |
| 2007 | 7,0 | 19 | 1,1 | 1,6 | 5,4 | 5,9 |
| 2008 | 38,4 | 111 | 30,9 | 26,1 | 12,3 | 7,5 |
| 2009 | 41,4 | 112 | 25,4 | 22,6 | 18,8 | 16,0 |
| 2010 | 29,3 | 138 | 20,5 | 24,9 | 4,4 | 8,8 |
| **DE** | | | | | | |
| 2007 | 33,3 | 10 | 2,0 | 1,8 | 31,5 | 31,3 |
| 2008 | 87,7 | 29 | 41,7 | 38,0 | 49,7 | 46,0 |
| 2009 | 87,1 | 30 | 31,6 | 37,4 | 49,7 | 55,5 |
| 2010 | 48,5 | 17 | 14,7 | 26,7 | 21,8 | 33,8 |
| **IE** | | | | | | |
| 2007 | 1,0 | 7 | 0,1 | 0,1 | 0,9 | 0,9 |
| 2008 | 2,2 | 15 | 1,3 | 1,4 | 0,8 | 0,9 |
| 2009 | 1,7 | 12 | 0,6 | 0,8 | 0,9 | 1,1 |
| 2010 | 1,2 | 9 | 0,2 | 0,4 | 0,8 | 1,0 |

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| | $CO_2$ abatement | | Impact ETS [Mio $tCO_2$] | | Impact RES-E [Mio $tCO_2$] | |
|---|---|---|---|---|---|---|
| | [Mio $tCO_2$] | [%] | w/o RES-E | w/ RES-E | w/o ETS | w/ ETS |
| **IT** | | | | | | |
| 2007 | 8,0 | 6 | -0,5 | -0,5 | 8,5 | 8,5 |
| 2008 | 4,8 | 4 | -6,2 | -3,2 | 8,0 | 11,0 |
| 2009 | 10,1 | 7 | -2,3 | -1,6 | 11,7 | 12,4 |
| 2010 | 14,7 | 11 | -3,8 | -4,6 | 19,3 | 18,5 |
| **LU** | | | | | | |
| 2007 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2008 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2009 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2010 | 0 | 0 | 0 | 0 | 0 | 0 |
| **NL** | | | | | | |
| 2007 | 9,5 | 18 | 0,1 | 0,2 | 9,3 | 9,4 |
| 2008 | 7,0 | 14 | -1,2 | 0,1 | 6,9 | 8,2 |
| 2009 | 7,3 | 15 | 0,2 | -0,8 | 8,1 | 7,1 |
| 2010 | 9,3 | 19 | -0,2 | -1,2 | 10,5 | 9,5 |
| **PT** | | | | | | |
| 2007 | 2,8 | 14 | 0,1 | 0,2 | 2,6 | 2,7 |
| 2008 | 5,3 | 27 | 0,7 | 1,8 | 3,5 | 4,6 |
| 2009 | 7,5 | 43 | 2,4 | 3,7 | 3,8 | 5,1 |
| 2010 | 7,0 | 40 | 2,1 | 2,9 | 4,1 | 4,9 |
| **ES** | | | | | | |
| 2007 | 16,9 | 14 | 0,6 | 0,6 | 16,3 | 16,3 |
| 2008 | 25,8 | 24 | 7,1 | 9,2 | 16,6 | 18,7 |
| 2009 | 36,7 | 40 | 12,9 | 15,4 | 21,3 | 23,8 |
| 2010 | 31,0 | 40 | 6,1 | 7,5 | 23,5 | 24,9 |
| **UK** | | | | | | |
| 2007 | 12,4 | 6 | 1,7 | 2,7 | 9,7 | 10,7 |
| 2008 | 59,2 | 31 | 44,4 | 47,3 | 11,9 | 14,8 |
| 2009 | 70,5 | 40 | 52,8 | 55,5 | 15,0 | 17,7 |
| 2010 | 72,9 | 42 | 53,0 | 54,6 | 18,3 | 19,9 |

TABLE A.2: Simulated $CO_2$ abatement in the electricity sector due to RES-E deployment and EU ETS.

## A.3 Net cross border transmission

Net annual cross border transmission data are displayed for MS12 and each country, for each year from 2007 to 2010 and for each scenario. A net importer is characterized by a negative net cross border transmission and a net exporter by a positive net cross border transmission.

| [TWh] | 2007 | | 2008 | | 2009 | | 2010 | |
|---|---|---|---|---|---|---|---|---|
| | ETS | No ETS | ETS | No ETS | ETS | No ETS | ETS | No ETS |
| **AT** | | | | | | | | |
| RES-E | -8,7 | -8,6 | -7,6 | -7,3 | -5,5 | -5,2 | -7,7 | -7,3 |
| No RES-E | -11,9 | -11,9 | -11,8 | -11,6 | -9,6 | -9,4 | -12,0 | -11,7 |
| **BE** | | | | | | | | |
| RES-E | -7,6 | -7,9 | -10,0 | -16,4 | -6,1 | -13,9 | -4,2 | -10,7 |
| No RES-E | -4,8 | -5,0 | -8,5 | -13,5 | -4,1 | -10,0 | 0,3 | -4,3 |
| **DK** | | | | | | | | |
| RES-E | 1,4 | 1,9 | 5,7 | 5,8 | 6,4 | 6,8 | 7,4 | 8,2 |
| No RES-E | 3,4 | 3,7 | -2,8 | -2,5 | -3,0 | -3,0 | -1,7 | -1,7 |
| **FR** | | | | | | | | |
| RES-E | 58,4 | 59,8 | 48,8 | 72,9 | 60,4 | 83,2 | 66,3 | 91,2 |
| No RES-E | 54,8 | 55,8 | 46,3 | 75,2 | 64,6 | 89,4 | 61,1 | 81,2 |
| **DE** | | | | | | | | |
| RES-E | 31,4 | 32,1 | 26,1 | 49,4 | 5,5 | 27,3 | -8,7 | 7,4 |
| No RES-E | 7,7 | 9,0 | 13,6 | 35,3 | -2,2 | 10,4 | -33,9 | -26,1 |
| **IE** | | | | | | | | |
| RES-E | -2,6 | -2,7 | -2,8 | -3,2 | -1,8 | -3,4 | -1,0 | -2,8 |
| No RES-E | -2,6 | -2,6 | -2,9 | -3,3 | -1,7 | -3,4 | -1,0 | -3,0 |
| **IT** | | | | | | | | |
| RES-E | -33,9 | -35,6 | -25,2 | -42,3 | -27,6 | -41,5 | -24,4 | -39,3 |
| No RES-E | -26,7 | -28,5 | -14,1 | -36,3 | -23,0 | -34,4 | -1,6 | -14,5 |
| **LU** | | | | | | | | |
| RES-E | -3,6 | -3,6 | -3,2 | -3,2 | -3,5 | -3,6 | -3,7 | -3,7 |
| No RES-E | -3,8 | -3,8 | -3,4 | -3,4 | -3,7 | -3,7 | -3,9 | -3,9 |
| **NL** | | | | | | | | |
| RES-E | -15,7 | -16,1 | -9,5 | -20,6 | -7,6 | -19,7 | -8,8 | -18,2 |
| No RES-E | -2,1 | -2,6 | -3,3 | -12,7 | -4,2 | -11,5 | 2,6 | -2,0 |
| **PT** | | | | | | | | |
| RES-E | -7,9 | -7,9 | -9,0 | -8,2 | -7,0 | -5,9 | -3,6 | -2,8 |
| No RES-E | -9,0 | -8,8 | -9,3 | -9,1 | -8,0 | -7,0 | -4,2 | -3,8 |

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| [TWh] | 2007 | | 2008 | | 2009 | | 2010 | |
|---|---|---|---|---|---|---|---|---|
| | ETS | No ETS | ETS | No ETS | ETS | No ETS | ETS | No ETS |
| **ES** | | | | | | | | |
| RES-E | 4,1 | 3,6 | 7,2 | -0,2 | 5,8 | 0,6 | 2,0 | -3,2 |
| No RES-E | 6,4 | 6,0 | 7,5 | 0,7 | 6,5 | 1,3 | 2,0 | -2,1 |
| **UK** | | | | | | | | |
| RES-E | -0,8 | -0,4 | -3,8 | -10,0 | -1,6 | -7,2 | 5,9 | 0,7 |
| No RES-E | 3,6 | 3,7 | 5,9 | -2,0 | 6,6 | -0,4 | 12,6 | 12,0 |

TABLE A.3: Simulated annual net cross border transmission.

## A.4 $CO_2$ intensity of electricity generation

$CO_2$ intensity of electricity generation is displayed for MS12 and each country, for each year from 2007 to 2010 and for each scenario. $CO_2$ intensity of electricity generation is determined as annual $CO_2$ emissions divided by annual electricity generation.

| $[\frac{tCO_2}{MWh}]$ | 2007 | | 2008 | | 2009 | | 2010 | |
|---|---|---|---|---|---|---|---|---|
| | ETS | No ETS | ETS | No ETS | ETS | No ETS | ETS | No ETS |
| **MS12** | | | | | | | | |
| RES-E | 0,396 | 0,398 | 0,373 | 0,423 | 0,356 | 0,410 | 0,342 | 0,386 |
| No RES-E | 0,437 | 0,439 | 0,420 | 0,469 | 0,414 | 0,464 | 0,393 | 0,430 |
| **AT** | | | | | | | | |
| RES-E | 0,275 | 0,275 | 0,267 | 0,272 | 0,277 | 0,282 | 0,261 | 0,265 |
| No RES-E | 0,295 | 0,296 | 0,294 | 0,298 | 0,305 | 0,308 | 0,287 | 0,290 |
| **BE** | | | | | | | | |
| RES-E | 0,208 | 0,209 | 0,202 | 0,205 | 0,203 | 0,205 | 0,207 | 0,214 |
| No RES-E | 0,233 | 0,234 | 0,232 | 0,236 | 0,239 | 0,243 | 0,245 | 0,251 |
| **DK** | | | | | | | | |
| RES-E | 0,705 | 0,710 | 0,603 | 0,603 | 0,589 | 0,592 | 0,583 | 0,587 |
| No RES-E | 0,984 | 0,987 | 0,790 | 0,790 | 0,793 | 0,793 | 0,788 | 0,788 |
| **FR** | | | | | | | | |
| RES-E | 0,071 | 0,074 | 0,065 | 0,109 | 0,067 | 0,104 | 0,071 | 0,110 |
| No RES-E | 0,083 | 0,085 | 0,079 | 0,130 | 0,095 | 0,135 | 0,087 | 0,120 |
| **DE** | | | | | | | | |
| RES-E | 0,705 | 0,710 | 0,603 | 0,603 | 0,589 | 0,592 | 0,583 | 0,587 |
| No RES-E | 0,984 | 0,987 | 0,790 | 0,790 | 0,793 | 0,793 | 0,788 | 0,788 |
| **IE** | | | | | | | | |
| RES-E | 0,579 | 0,585 | 0,568 | 0,635 | 0,528 | 0,598 | 0,502 | 0,557 |
| No RES-E | 0,616 | 0,620 | 0,608 | 0,670 | 0,568 | 0,634 | 0,541 | 0,593 |
| **IT** | | | | | | | | |
| RES-E | 0,472 | 0,473 | 0,446 | 0,461 | 0,458 | 0,473 | 0,433 | 0,439 |
| No RES-E | 0,489 | 0,490 | 0,465 | 0,479 | 0,491 | 0,502 | 0,459 | 0,466 |
| **LU** | | | | | | | | |
| RES-E | 0,340 | 0,340 | 0,365 | 0,365 | 0,337 | 0,337 | 0,343 | 0,343 |
| No RES-E | 0,357 | 0,357 | 0,389 | 0,389 | 0,356 | 0,356 | 0,359 | 0,359 |
| **NL** | | | | | | | | |
| RES-E | 0,522 | 0,526 | 0,484 | 0,542 | 0,463 | 0,514 | 0,453 | 0,484 |
| No RES-E | 0,542 | 0,545 | 0,529 | 0,565 | 0,513 | 0,552 | 0,490 | 0,507 |
| **PT** | | | | | | | | |
| RES-E | 0,458 | 0,461 | 0,460 | 0,491 | 0,379 | 0,448 | 0,343 | 0,393 |
| No RES-E | 0,529 | 0,532 | 0,569 | 0,581 | 0,498 | 0,539 | 0,443 | 0,479 |

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| $[\frac{tCO_2}{MWh}]$ | 2007 | | 2008 | | 2009 | | 2010 | |
|---|---|---|---|---|---|---|---|---|
| | ETS | No ETS | ETS | No ETS | ETS | No ETS | ETS | No ETS |
| **ES** | | | | | | | | |
| RES-E | 0,402 | 0,405 | 0,357 | 0,398 | 0,318 | 0,378 | 0,272 | 0,304 |
| No RES-E | 0,454 | 0,456 | 0,420 | 0,454 | 0,399 | 0,451 | 0,361 | 0,387 |
| **UK** | | | | | | | | |
| RES-E | 0,533 | 0,540 | 0,529 | 0,672 | 0,494 | 0,659 | 0,472 | 0,628 |
| No RES-E | 0,556 | 0,560 | 0,555 | 0,691 | 0,532 | 0,688 | 0,516 | 0,658 |

TABLE A.4: Simulated $CO_2$ intensity of electricity generation.

## A.5 Fuel shares in the electricity sector

Coal share en gas share are displayed for MS12 and each country, for each year from 2007 to 2010 and for each scenario. Fuel shares are expressed as a percentage of total electricity generation. Coal share and gase share include cogeneration plants. Gas share includes combined cycle power plants and gas turbine units.

| [%] | OBS scenario | | RES scenario | | ETS scenario | | NOPOL scenario | |
|---|---|---|---|---|---|---|---|---|
| | coal | gas | coal | gas | coal | gas | coal | gas |
| **MS12** | | | | | | | | |
| 2007 | 19,4 | 27,3 | 19,9 | 26,8 | 21,6 | 31,5 | 22,0 | 31,1 |
| 2008 | 17,4 | 28,7 | 25,2 | 20,3 | 20,1 | 33,0 | 27,5 | 24,8 |
| 2009 | 17,0 | 28,8 | 26,3 | 19,3 | 21,1 | 32,9 | 29,4 | 24,4 |
| 2010 | 16,9 | 27,9 | 24,5 | 20,3 | 19,2 | 34,8 | 25,4 | 28,6 |
| **AT** | | | | | | | | |
| 2007 | 9,5 | 28,8 | 9,5 | 28,8 | 9,7 | 28,8 | 9,7 | 28,8 |
| 2008 | 8,8 | 27,6 | 9,5 | 27,6 | 9,2 | 27,6 | 9,7 | 27,6 |
| 2009 | 8,4 | 31,7 | 9,0 | 31,7 | 9,0 | 31,7 | 9,3 | 31,7 |
| 2010 | 8,8 | 28,1 | 9,4 | 28,1 | 9,1 | 28,1 | 9,5 | 28,1 |
| **BE** | | | | | | | | |
| 2007 | 7,6 | 29,3 | 7,9 | 28,6 | 8,5 | 35,0 | 8,6 | 34,7 |
| 2008 | 6,3 | 31,4 | 9,8 | 20,0 | 7,5 | 36,3 | 10,1 | 27,4 |
| 2009 | 7,0 | 31,7 | 10,9 | 18,6 | 9,0 | 36,6 | 11,9 | 26,6 |
| 2010 | 8,1 | 30,1 | 11,7 | 18,8 | 9,3 | 39,2 | 11,9 | 31,3 |
| **DK** | | | | | | | | |
| 2007 | 61,3 | 4,9 | 62,7 | 4,7 | 92,3 | 5,2 | 93,6 | 4,9 |
| 2008 | 64,6 | 4,1 | 64,9 | 4,1 | 65,3 | 4,1 | 65,3 | 4,1 |
| 2009 | 63,5 | 3,9 | 64,3 | 3,9 | 65,3 | 4,3 | 65,3 | 4,3 |
| 2010 | 63,5 | 3,9 | 65,3 | 3,9 | 67,4 | 6,1 | 67,4 | 6,1 |
| **FR** | | | | | | | | |
| 2007 | 4,8 | 2,9 | 5,1 | 2,9 | 5,7 | 2,9 | 5,9 | 2,9 |
| 2008 | 4,3 | 2,9 | 8,5 | 2,9 | 5,4 | 3,0 | 10,2 | 2,9 |
| 2009 | 5,3 | 2,8 | 9,5 | 2,7 | 8,3 | 2,8 | 12,8 | 2,8 |
| 2010 | 6,1 | 2,6 | 10,5 | 2,6 | 7,7 | 2,7 | 11,2 | 2,6 |
| **DE** | | | | | | | | |
| 2007 | 22,0 | 14,7 | 22,3 | 14,4 | 26,0 | 17,6 | 26,4 | 17,4 |
| 2008 | 18,6 | 15,6 | 27,0 | 11,3 | 25,1 | 19,0 | 33,9 | 13,6 |
| 2009 | 18,4 | 16,0 | 26,9 | 11,2 | 26,6 | 19,1 | 33,8 | 14,1 |
| 2010 | 18,3 | 16,0 | 24,0 | 13,0 | 21,5 | 21,6 | 24,7 | 19,7 |

*Continued on next page*

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| [%] | OBS scenario | | RES scenario | | ETS scenario | | NOPOL scenario | |
|---|---|---|---|---|---|---|---|---|
| | coal | gas | coal | gas | coal | gas | coal | gas |
| **IE** | | | | | | | | |
| 2007 | 16,5 | 59,1 | 17,3 | 57,7 | 17,7 | 64,5 | 18,4 | 63,7 |
| 2008 | 16,0 | 58,3 | 24,8 | 45,0 | 17,2 | 64,2 | 24,9 | 51,5 |
| 2009 | 14,2 | 64,0 | 24,7 | 47,2 | 15,7 | 70,5 | 24,8 | 54,2 |
| 2010 | 13,4 | 67,9 | 21,6 | 52,9 | 14,6 | 74,2 | 21,8 | 59,6 |
| **IT** | | | | | | | | |
| 2007 | 20,0 | 58,0 | 20,2 | 57,2 | 20,1 | 63,9 | 20,3 | 63,1 |
| 2008 | 19,6 | 55,8 | 21,4 | 47,1 | 20,0 | 62,7 | 21,4 | 52,6 |
| 2009 | 20,1 | 57,1 | 22,6 | 49,4 | 21,3 | 63,3 | 22,6 | 57,5 |
| 2010 | 21,3 | 53,5 | 22,5 | 47,4 | 21,4 | 67,2 | 22,5 | 61,9 |
| **LU** | | | | | | | | |
| 2007 | 0 | 90,9 | 0 | 90,9 | 0 | 90,9 | 0 | 90,9 |
| 2008 | 0 | 88,7 | 0 | 88,7 | 0 | 88,7 | 0 | 88,7 |
| 2009 | 0 | 89,1 | 0 | 89,1 | 0 | 89,1 | 0 | 89,1 |
| 2010 | 0 | 91,5 | 0 | 91,5 | 0 | 91,5 | 0 | 91,5 |
| **NL** | | | | | | | | |
| 2007 | 22,9 | 66,4 | 23,5 | 65,3 | 24,7 | 83,7 | 25,1 | 82,9 |
| 2008 | 19,5 | 69,2 | 27,2 | 51,0 | 23,7 | 77,5 | 28,0 | 64,6 |
| 2009 | 19,4 | 67,2 | 26,6 | 48,6 | 23,4 | 73,5 | 28,6 | 61,4 |
| 2010 | 18,9 | 67,2 | 23,2 | 54,1 | 20,6 | 83,5 | 23,5 | 76,5 |
| **PT** | | | | | | | | |
| 2007 | 25,8 | 27,8 | 26,3 | 27,4 | 28,3 | 34,4 | 28,8 | 34,2 |
| 2008 | 23,9 | 32,6 | 28,0 | 27,9 | 27,2 | 39,1 | 28,6 | 37,1 |
| 2009 | 18,6 | 32,5 | 30,7 | 22,1 | 26,0 | 40,6 | 32,4 | 35,0 |
| 2010 | 17,7 | 29,5 | 26,5 | 22,3 | 21,1 | 44,4 | 27,5 | 38,0 |
| **ES** | | | | | | | | |
| 2007 | 17,9 | 32,2 | 18,4 | 31,5 | 19,3 | 41,9 | 19,8 | 41,3 |
| 2008 | 12,8 | 37,8 | 19,6 | 27,8 | 14,7 | 48,0 | 19,7 | 39,3 |
| 2009 | 11,5 | 35,8 | 22,6 | 22,7 | 15,3 | 46,8 | 24,5 | 35,3 |
| 2010 | 11,2 | 30,6 | 17,1 | 22,9 | 13,4 | 46,7 | 18,1 | 40,5 |
| **UK** | | | | | | | | |
| 2007 | 35,8 | 41,7 | 36,9 | 40,8 | 37,4 | 45,1 | 38,0 | 44,4 |
| 2008 | 34,5 | 44,9 | 56,3 | 20,6 | 36,7 | 49,6 | 57,2 | 25,8 |
| 2009 | 32,0 | 47,0 | 59,2 | 18,3 | 35,5 | 50,9 | 61,2 | 23,3 |
| 2010 | 29,1 | 50,0 | 55,0 | 22,8 | 33,2 | 53,6 | 57,0 | 29,6 |

Table A.5: Simulated coal share and gas share.

## A.6 Impact of different types of RES-E on $CO_2$ emissions

$CO_2$ emission data are displayed for MS12 and each country, for each year from 2007 to 2010 and in absence of wind energy, solar energy and bio-energy.

| [Mio $tCO_2$] | OBS | No wind | No sun | No bio | No RES-E |
|---|---|---|---|---|---|
| **MS12** | | | | | |
| 2007 | 957 | 1022 | 960 | 992 | 1057 |
| 2008 | 906 | 979 | 911 | 944 | 1022 |
| 2009 | 874 | 960 | 883 | 920 | 1017 |
| 2010 | 854 | 931 | 866 | 895 | 983 |
| **AT** | | | | | |
| 2007 | 14,2 | 14,2 | 14,2 | 14,2 | 14,3 |
| 2008 | 14,2 | 14,4 | 14,3 | 14,3 | 14,5 |
| 2009 | 15,7 | 15,9 | 15,7 | 15,9 | 16,0 |
| 2010 | 14,0 | 14,1 | 14,0 | 14,0 | 14,2 |
| **BE** | | | | | |
| 2007 | 17,7 | 19,1 | 17,7 | 18,9 | 20,4 |
| 2008 | 16,6 | 18,0 | 16,7 | 17,6 | 19,4 |
| 2009 | 17,1 | 18,7 | 17,4 | 18,5 | 20,7 |
| 2010 | 17,6 | 19,6 | 18,0 | 19,1 | 21,9 |
| **DK** | | | | | |
| 2007 | 24,8 | 33,0 | 24,9 | 27,4 | 36,5 |
| 2008 | 22,7 | 22,9 | 22,7 | 22,8 | 23,0 |
| 2009 | 23,9 | 24,5 | 24,2 | 24,2 | 24,6 |
| 2010 | 26,1 | 27,8 | 26,1 | 26,5 | 28,1 |
| **FR** | | | | | |
| 2007 | 37,7 | 41,9 | 38,1 | 40,7 | 43,6 |
| 2008 | 34,7 | 38,9 | 34,8 | 37,1 | 42,2 |
| 2009 | 37,0 | 45,8 | 37,8 | 42,7 | 53,0 |
| 2010 | 40,5 | 46,1 | 40,8 | 44,2 | 49,3 |
| **DE** | | | | | |
| 2007 | 321 | 342 | 323 | 334 | 352 |
| 2008 | 300 | 328 | 302 | 317 | 346 |
| 2009 | 290 | 321 | 293 | 310 | 345 |
| 2010 | 290 | 306 | 292 | 301 | 323 |
| **IE** | | | | | |
| 2007 | 14,7 | 15,5 | 14,7 | 14,8 | 15,6 |
| 2008 | 14,5 | 15,2 | 14,5 | 14,6 | 15,4 |
| 2009 | 13,7 | 14,6 | 13,7 | 13,8 | 14,8 |
| 2010 | 13,2 | 14,0 | 13,2 | 13,3 | 14,2 |

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| [Mio $tCO_2$] | OBS | No wind | No sun | No bio | No RES-E |
|---|---|---|---|---|---|
| **IT** | | | | | |
| 2007 | 141 | 145 | 141 | 145 | 150 |
| 2008 | 136 | 141 | 137 | 141 | 147 |
| 2009 | 138 | 143 | 139 | 144 | 150 |
| 2010 | 134 | 143 | 136 | 143 | 153 |
| **LU** | | | | | |
| 2007 | 1,1 | 1,1 | 1,1 | 1,1 | 1,1 |
| 2008 | 0,9 | 0,9 | 0,9 | 0,9 | 0,9 |
| 2009 | 0,9 | 0,9 | 0,9 | 0,9 | 0,9 |
| 2010 | 1,1 | 1,1 | 1,1 | 1,1 | 1,1 |
| **NL** | | | | | |
| 2007 | 52,8 | 58,0 | 53,0 | 56,0 | 62,2 |
| 2008 | 51,1 | 56,1 | 51,5 | 54,1 | 59,3 |
| 2009 | 49,7 | 53,5 | 50,1 | 52,4 | 56,8 |
| 2010 | 49,0 | 54,1 | 50,1 | 52,5 | 58,5 |
| **PT** | | | | | |
| 2007 | 20,2 | 22,2 | 20,3 | 20,8 | 22,9 |
| 2008 | 20,0 | 23,8 | 20,1 | 20,8 | 24,6 |
| 2009 | 17,6 | 21,7 | 17,8 | 18,3 | 22,7 |
| 2010 | 17,6 | 21,6 | 18,1 | 18,3 | 22,5 |
| **ES** | | | | | |
| 2007 | 118 | 132 | 118 | 120 | 134 |
| 2008 | 106 | 121 | 107 | 107 | 125 |
| 2009 | 93 | 113 | 95 | 94 | 116 |
| 2010 | 77 | 97 | 81 | 79 | 102 |
| **UK** | | | | | |
| 2007 | 194 | 198 | 194 | 199 | 204 |
| 2008 | 189 | 197 | 190 | 196 | 204 |
| 2009 | 178 | 188 | 179 | 186 | 196 |
| 2010 | 175 | 187 | 175 | 183 | 195 |

TABLE A.6: Simulated $CO_2$ emissions in the electricity sector in absence of RES-E.

# Appendix B

# Simulation results based on the ETS-cap assumption

The results presented in this appendix follow from simulations based on the *ETS-cap assumption*, meaning that EU ETS is modeled as an exogenous $CO_2$ emission cap imposed on the electricity generators. The emission cap is set to historical levels for both scenarios, i.e. 957 million $tCO_2$ in 2007, 906 million $tCO_2$ in 2008 and 854 million $tCO_2$ in 2010. 2009 is not considered as historical emission levels of that year can not be reached without RES-E deployment.

## B.1 $CO_2$ emissions in the electricity sector

Emission data are displayed for MS12 and each country, for 2007,2008 and 2010 and the OBS scenario and ETS scenario.

| [Mio $tCO_2$] | OBS scenario | ETS scenario |
|---|---|---|
| **2007** | | |
| MS12 | 957,2 | 957,2 |
| AT | 14,2 | 14,2 |
| BE | 17,7 | 21,2 |
| DK | 24,8 | 24,9 |
| FR | 37,7 | 17,1 |
| DE | 321,4 | 326,6 |
| IE | 14,7 | 14,9 |
| IT | 141,1 | 158,9 |
| LU | 1,1 | 1,1 |
| NL | 52,8 | 62,2 |
| PT | 20,2 | 22,1 |
| ES | 117,9 | 124,4 |

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| [Mio $tCO_2$] | OBS scenario | ETS scenario |
|---|---|---|
| UK | 193,6 | 169,5 |
| CH | 1,0 | 1,0 |
| **2008** | | |
| MS12 | 906,4 | 906,4 |
| AT | 14,2 | 16,0 |
| BE | 16,6 | 20,7 |
| DK | 22,7 | 23,2 |
| FR | 34,7 | 21,3 |
| DE | 300,1 | 307,2 |
| IE | 14,5 | 14,6 |
| IT | 136,3 | 147,7 |
| LU | 0,9 | 0,9 |
| NL | 51,1 | 56,9 |
| PT | 20,0 | 23,6 |
| ES | 105,9 | 109,9 |
| UK | 189,4 | 164,2 |
| CH | 1,1 | 1,1 |
| **2010** | | |
| MS12 | 854,4 | 854,4 |
| AT | 14,0 | 19,3 |
| BE | 17,6 | 27,4 |
| DK | 26,1 | 26,1 |
| FR | 40,5 | 18,7 |
| DE | 289,5 | 288,9 |
| IE | 13,2 | 13,6 |
| IT | 134,0 | 144,9 |
| LU | 1,1 | 1,1 |
| NL | 49,0 | 58,3 |
| PT | 17,6 | 16,6 |
| ES | 77,4 | 89,5 |
| UK | 174,6 | 150,1 |
| CH | 1,2 | 1,2 |

TABLE B.1: Simulated $CO_2$ emissions in the electricity sector under a $CO_2$ emission cap.

## B.2 Electricity generation

Electricity generation data are displayed for MS12 and each country, for 2007, 2008 and 2010 and the OBS scenario and ETS scenario.

| [TWh] | OBS scenario | | | | | ETS scenario | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | coal | gas | oil | RES | total | coal | gas | oil | RES | total |
| **2007** | | | | | | | | | | |
| MS12 | 468,4 | 662,3 | 64,3 | 156,2 | 2466,3 | 363,1 | 922,9 | 64,6 | 0,7 | 2466,4 |
| AT | 4,9 | 14,8 | 1,6 | 3,3 | 51,5 | 4,8 | 14,9 | 1,6 | 0 | 48,3 |
| BE | 6,5 | 24,9 | 0,9 | 2,8 | 84,9 | 5,6 | 35,4 | 0,9 | 0 | 91,6 |
| DK | 21,5 | 1,7 | 1,0 | 9,1 | 35,2 | 21,0 | 3,1 | 1,0 | 0 | 26,8 |
| FR | 25,5 | 15,3 | 4,0 | 8,6 | 531,3 | 7,6 | 15,5 | 4,0 | 0 | 504,9 |
| DE | 129,2 | 86,3 | 8,7 | 64,5 | 588,2 | 119,4 | 125,3 | 8,7 | 0 | 552,8 |
| IE | 4,2 | 15,0 | 1,2 | 1,7 | 25,4 | 2,6 | 19,3 | 1,2 | 0 | 26,4 |
| IT | 59,7 | 173,4 | 16,5 | 10,6 | 298,8 | 57,3 | 216,3 | 16,5 | 0 | 328,8 |
| LU | 0 | 2,9 | 0 | 0,2 | 3,2 | 0 | 2,9 | 0 | 0 | 3,0 |
| NL | 23,1 | 67,1 | 0 | 5,8 | 101,1 | 18,8 | 99,7 | 0 | 0 | 123,5 |
| PT | 11,4 | 12,3 | 5,4 | 5,3 | 44,1 | 11,4 | 16,1 | 5,7 | 0 | 43,0 |
| ES | 52,4 | 94,4 | 20,7 | 30,3 | 293,4 | 36,7 | 146,9 | 20,7 | 0 | 299,8 |
| UK | 130,0 | 151,5 | 4,3 | 13,3 | 363,0 | 78,0 | 224,9 | 4,3 | 0 | 371,1 |
| CH | 0 | 2,6 | 0 | 0,7 | 46,3 | 0 | 2,6 | 0 | 0,7 | 46,3 |
| **2008** | | | | | | | | | | |
| MS12 | 422,2 | 699,5 | 64,5 | 176,2 | 2474,2 | 281,4 | 1009,9 | 70,5 | 0,6 | 2474,3 |
| AT | 4,7 | 14,7 | 1,5 | 4,4 | 53,4 | 4,6 | 17,9 | 1,5 | 0 | 52,1 |
| BE | 5,2 | 25,9 | 0,3 | 3,6 | 82,3 | 3,3 | 38,2 | 0,4 | 0 | 89,2 |
| DK | 24,3 | 1,5 | 1,1 | 8,9 | 37,6 | 24,6 | 1,6 | 1,4 | 0 | 29,4 |
| FR | 22,8 | 15,8 | 5,1 | 9,8 | 535,3 | 8,1 | 16,3 | 8,2 | 0 | 514,5 |
| DE | 108,5 | 91,1 | 9,0 | 69,8 | 582,3 | 91,9 | 144,2 | 10,2 | 0 | 550,2 |
| IE | 4,1 | 14,9 | 1,3 | 1,9 | 25,5 | 1,4 | 21,5 | 1,3 | 0 | 27,5 |
| IT | 59,8 | 170,7 | 16,0 | 11,9 | 305,8 | 40,3 | 240,0 | 13,7 | 0 | 341,5 |
| LU | 0 | 2,2 | 0 | 0,1 | 2,5 | 0 | 2,2 | 0 | 0 | 2,3 |
| NL | 20,5 | 73,1 | 0 | 6,9 | 105,6 | 18,1 | 91,7 | 0 | 0 | 114,9 |
| PT | 10,4 | 14,2 | 5,2 | 6,9 | 43,6 | 10,5 | 18,4 | 7,3 | 0 | 43,0 |
| ES | 38,1 | 112,1 | 20,8 | 36,2 | 296,5 | 11,3 | 179,9 | 20,8 | 0 | 301,3 |
| UK | 123,7 | 160,8 | 4,2 | 15,0 | 358,2 | 67,3 | 235,4 | 5,7 | 0 | 362,9 |
| CH | 0 | 2,6 | 0 | 0,6 | 45,6 | 0 | 2,6 | 0 | 0,6 | 45,6 |

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| [TWh] | OBS scenario | | | | | ETS scenario | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | coal | gas | oil | RES | total | coal | gas | oil | RES | total |
| **2010** | | | | | | | | | | |
| MS12 | 422,4 | 701,9 | 56,0 | 227,3 | 2545,9 | 158,5 | 1166,0 | 83,8 | 0,8 | 2547,4 |
| AT | 4,7 | 15,1 | 1,4 | 4,4 | 53,6 | 4,2 | 25,1 | 1,5 | 0 | 58,7 |
| BE | 6,8 | 25,5 | 0,7 | 4,2 | 84,8 | 0,6 | 56,4 | 0,8 | 0 | 105,3 |
| DK | 28,5 | 1,7 | 1,0 | 11,8 | 44,8 | 14,9 | 20,9 | 1,8 | 0 | 39,4 |
| FR | 34,6 | 15,0 | 3,2 | 14,7 | 568,2 | 5,6 | 15,7 | 8,5 | 0 | 530,9 |
| DE | 109,4 | 95,3 | 9,7 | 77,6 | 596,8 | 60,5 | 171,4 | 19,5 | 0 | 556,3 |
| IE | 3,5 | 17,8 | 0,3 | 2,0 | 26,2 | 0,4 | 24,5 | 0,5 | 0 | 28,0 |
| IT | 65,9 | 165,5 | 13,2 | 20,1 | 309,5 | 19,9 | 276,8 | 13,2 | 0 | 354,7 |
| LU | 0 | 3,0 | 0 | 0,2 | 3,3 | 0 | 3,0 | 0 | 0 | 3,1 |
| NL | 20,4 | 72,6 | 0 | 8,2 | 108,2 | 6,3 | 119,6 | 0 | 0 | 132,8 |
| PT | 9,1 | 15,2 | 4,2 | 10,0 | 51,4 | 0,8 | 29,3 | 4,4 | 0 | 47,6 |
| ES | 31,7 | 86,8 | 19,0 | 52,0 | 283,9 | 0,4 | 179,9 | 19,0 | 0 | 293,7 |
| UK | 107,8 | 185,3 | 3,3 | 21,7 | 370,3 | 44,9 | 240,1 | 14,5 | 0 | 351,8 |
| CH | 0 | 3,1 | 0 | 0,8 | 44,9 | 0 | 3,1 | 0 | 0,8 | 44,9 |

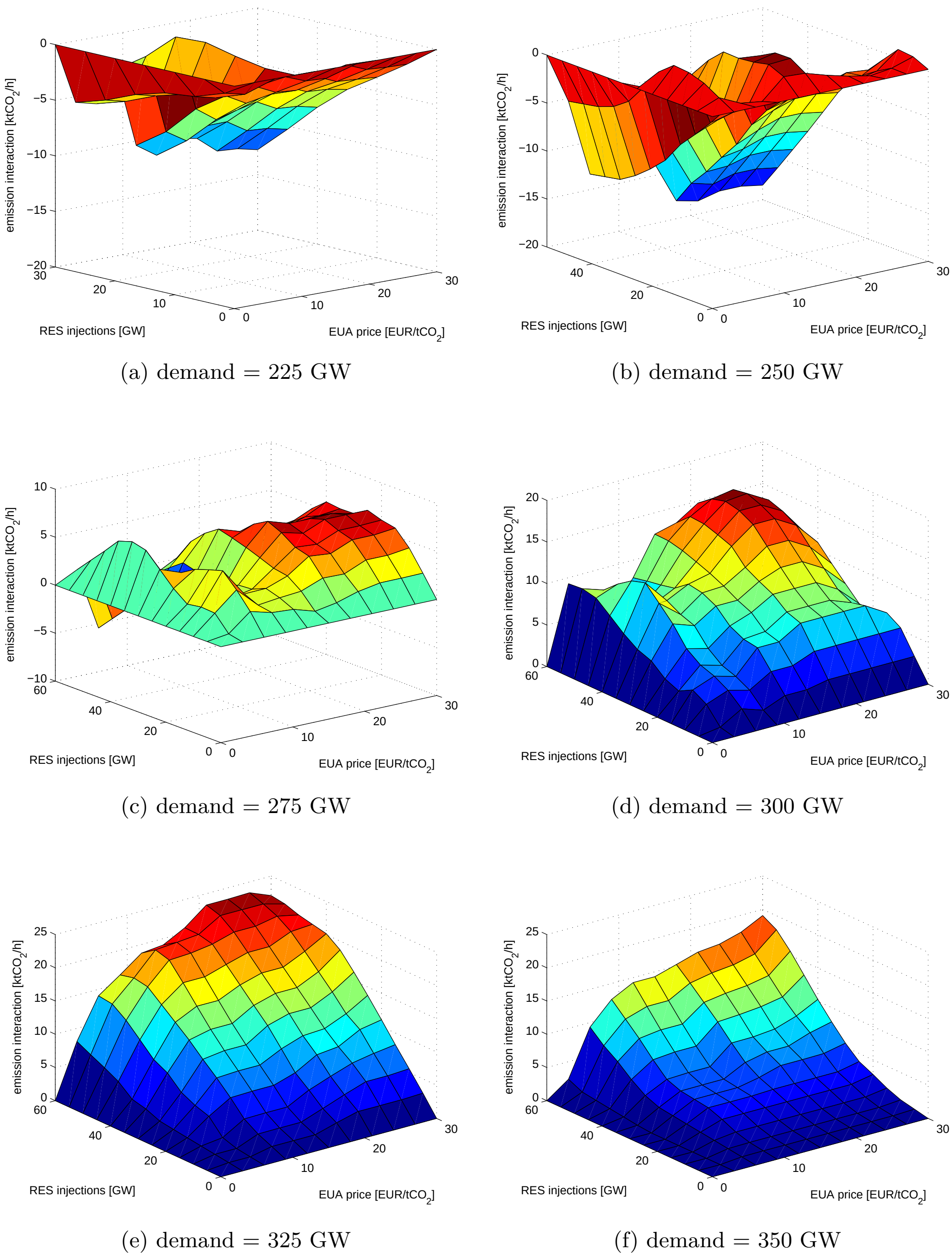
TABLE B.2: Simulated electricity generation under a $CO_2$ emission cap.

# Appendix C

# Simulation results: emission interaction effect

Figures C.1, C.2 and C.3 show the emission interaction effect between EU ETS and RES-E deployment as function of electricity demand, EUA price and RES-E injections and at historical fuel prices for respectively 2007, 2008 and 2009. A similar figure for 2010 is given at page 75.

Note that the figures result from a simulation based on the *ETS-price assumption*, meaning that EU ETS is modeled as an exogenous EUA price imposed on the electricity generators.




(a) demand = 225 GW

(b) demand = 250 GW

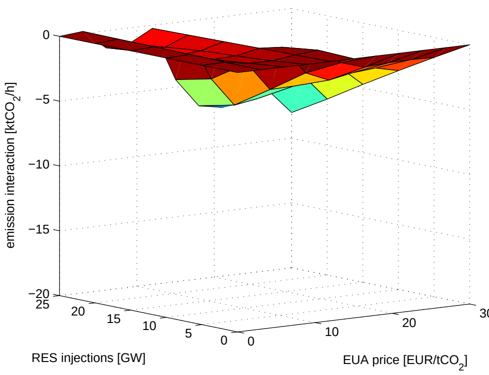
(c) demand = 275 GW

(d) demand = 300 GW

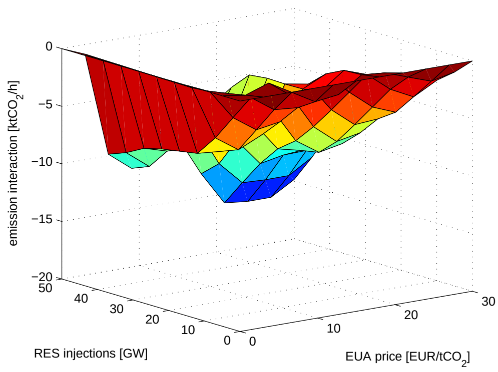
(e) demand = 325 GW

(f) demand = 350 GW

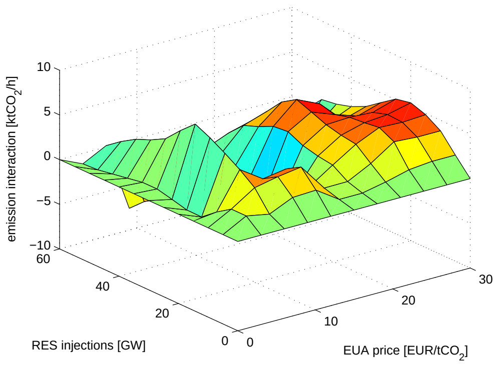
FIGURE C.1: Emission interaction effect as function of RES-E injections and EUA price for different electricity demand levels and average 2007 historical fuel prices (a coal price of 8,96 EUR/MWh$_{prim}$ and a natural gas price of 15,08 EUR/MWh$_{prim}$).



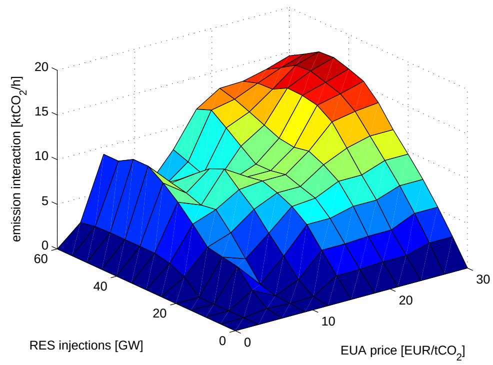

(a) demand = 225 GW



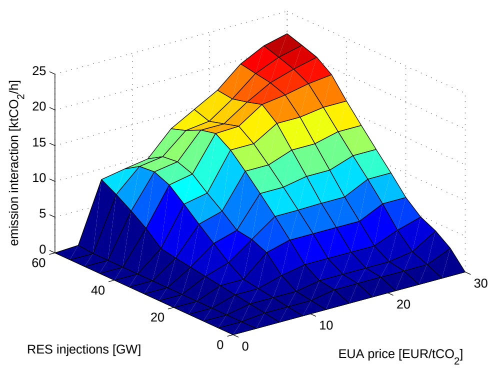

(b) demand = 250 GW



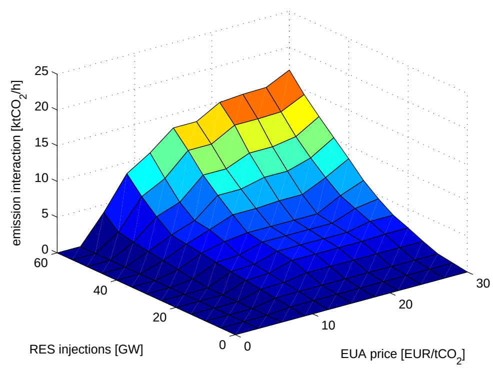

(c) demand = 275 GW




(d) demand = 300 GW

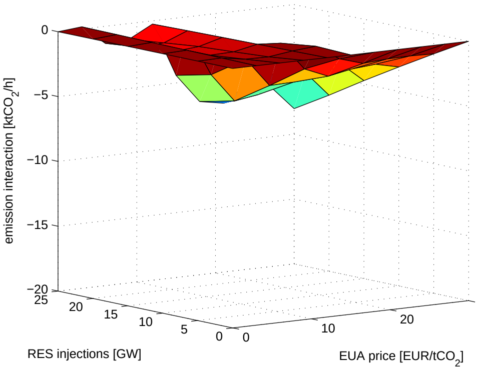



(e) demand = 325 GW

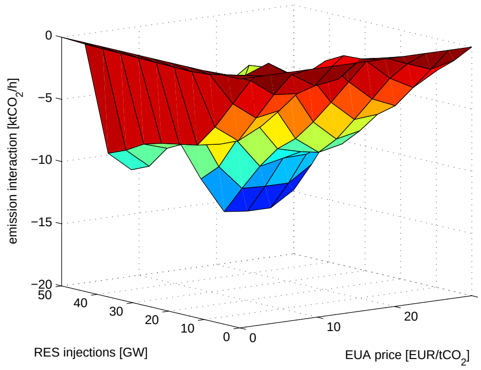



(f) demand = 350 GW

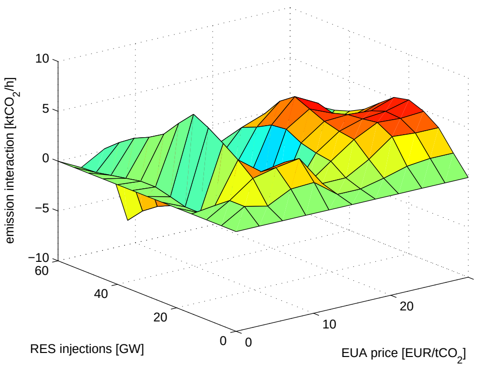
FIGURE C.2: Emission interaction effect as function of RES-E injections and EUA price for different electricity demand levels and average 2008 historical fuel prices (a coal price of 13,72 EUR/MWh$_{prim}$ and a natural gas price of 25,97 EUR/MWh$_{prim}$).



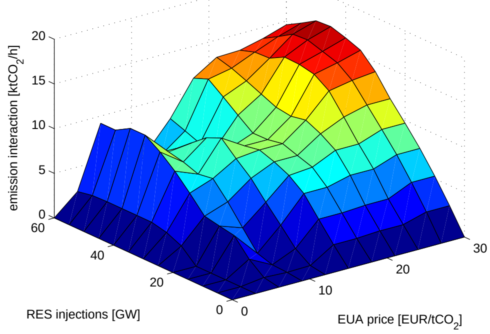

(a) demand = 225 GW



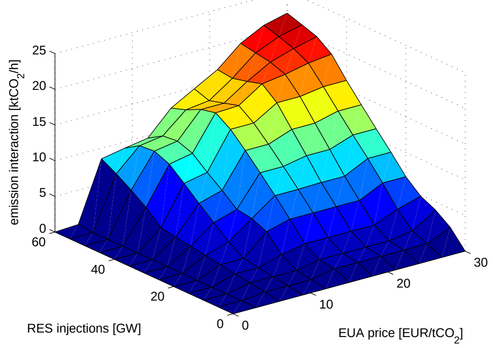

(b) demand = 250 GW



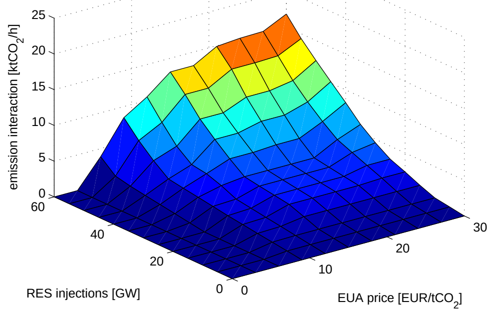

(c) demand = 275 GW




(d) demand = 300 GW




(e) demand = 325 GW




(f) demand = 350 GW

FIGURE C.3: Emission interaction effect as function of RES-E injections and EUA price for different electricity demand levels and average 2009 historical fuel prices (a coal price of 7,94 $EUR/MWh_{prim}$ and a natural gas price of 13,87 $EUR/MWh_{prim}$).

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