DISSERTATION

Modelling Emission Allowance Prices

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Abbreviation

AAU	Assigned Amount Unit
ADP	Ad-Hoc working Group on the Durban Platform for Enhanced Action
AR	Assessment Report
AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
AR6	Sixth Assessment Report
AVR	Accreditation and Verification Regulation
BAU	Business as Usual
CAC	Command and Control
CCA	California Carbon Allowance
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CH4	Methane
CITL	Community Independent Transaction Log
CLEF	Carbon Leakage Exposure Factor
CMP	Meetings of Parties of the Kyoto Protocol
CO2	Carbon Dioxide

COP	Conferences of the Parties
CPR	Commitment Period Reserve
CSCF	Cross-sectoral Correction Factor
EEA	European Economic Area
EEX	European Energy Exchange
EFTA	European Free Trade Association
EIT	Economies in Transition
ERU	Emission Reduction Unit
ET	Emission Trading
ETS	Emission Trading Scheme
EU	European Union
EUA	European Union Allowance
EUAA	European Union Aviation Allowance
EUTL	European Union Transaction Log
EXAA	Energy Exchange Austria
GCF	Green Climate Fund
GGAS	Greenhouse Gas Abatement Scheme
GHG	Greenhouse Gas
GWP	Global Warming Potentials
HAL	Historical Activity Level
HFC	Hydrofluorocarbon
IAA	Initial Assigned Amount
ICE	Intercontinental Exchange
INDC	Intended Nationally Determined Contribution

IPCC	Intergovernmental Panel on Climate Change
ITL	International Transaction Log
JI	Joint Implementation
KKT	Karush-Kuhn-Tucker
LRF	Linear Reduction Factor
LULUCF	Land Use, Land-use Change and Forestry
MBI	Market-based Instrument
MiFID	Markets in Financial Instruments Directive
MPE	Mean Pricing Error
MPR	Market Price of Risk
MRR	Monitoring and Reporting Regulation
MRV	Monitoring, Reporting and Verification
MSR	Market Stability Reserve
N2O	Nitrous Oxide
NAP	National Allocation Plan
NDC	Nationally Determined Contribution
NDRC	National Development and Reform Commission
NIM	National Implementation Measure
NOMX	NASDAQ OMX Commodities Europe
NYMEX	New York Mercantile Exchange
OECD	Organization for Economic Co-operation and Development
OTC	Over-The-Counter
PFC	Perfluorocarbon
RGGI	Regional Greenhouse Gas Initiative

ABBREVIATION

RMSE	Root Mean Squared Error
RMU	Removal Unit
SAR	Second Assessment Report
SDE	Stochastic Differential Equation
SF6	Sulphur Hexafluoride
SO2	Sulfur Dioxide
TAR	Third Assessment Report
TNAC	Total Number of Allowances in Circulation
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WCI	Western Climate Initiative
WMO	World Meteorological Organization

1

Introduction

1.1 Background of Climate Change and Emission Trading

Climate change is happening and will continue over decades to come. There is broad-based agreement within the scientific community that climate change is real, and scientists believe that human's activities, such as burning fossil fuels, industrial production, agriculture and deforestation, are the main cause of the current global warming. Actually, climate scientists have increased their understanding of the climate system, they are able to state with increasing certainty that the Earth's climate has changed beyond historic variability, and that human's activities are the main cause. This can be seen from the statements in the Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

The fourth IPCC's Assessment Report published in 2007 states that:

"Most of the observed increase in global average temperatures since the mid-20th century is very likely (90% confidence) due to the observed increase in anthropogenic greenhouse gas concentrations."(IPCC 07)

However, in the fifth IPCC's Assessment Report published in 2013, it concludes that:

"It is extremely likely (95% confidence) more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together." (IPCC 13)

The report also states that the greenhouse gas emissions contributed a global mean surface warming likely to be in the range of 0.5°C to 1.3°C over the period 1951 to 2010. If we keep the current human activities in a business as usual (BAU) scenario, the average temperature between 2080 and 2100 is very likely to be 2.6-4.8°C higher than today, so predicted the climate scientists in this report. Moreover, continued carbon emissions in the atmosphere will drive further heatwaves, sea level rise, melting ice and extreme weather. Therefore, to avoid the worst consequences of global warming, cutting substantial and sustained anthropogenic greenhouse gas emissions is required. This environmental issue is a significant challenge for the policy makers.

Research on policy instruments of reducing the greenhouse gas emissions begins in the sixties of the twentieth century. In the last 50 years, different possible solutions are widely studied and practiced. Basically, there are two main environmental policy instruments available to be implemented: the regulatory instrument and the marked-based instrument (MBI).

The regulatory instrument, also called the command and control regulation (CAC), can be defined as the direct regulation of an industry or activity by legislation that states what is permitted and what is illegal. (McMa 09) The command means that the standards by a government authority that must be complied with, while control signifies negative sanctions that may result from non-compliance. (BaCL 11) For the issue of reducing the greenhouse gas emissions, this means that the government sets legal limits on emission levels and controls the manner in which it is achieved. In practice, the command and control regulation is argued not as effective as a market-based approach, because emission sources diffuse and it is usually not possible for a command and control approach to be implemented in a cost efficient way. A simple example can be described as follows: it is relatively easy to regulate the emissions from 10 large coal burning power stations in a single country, but far less easy to monitor the emissions caused by millions of motorists or the effluent discharges from tens of thousands of farms across the world. (Evan 12)

By way of contrast, a market-based instrument differs from a command and control instrument and provides more flexibility and effectiveness on reducing the greenhouse gases. A market-based instrument is defined as instruments or regulations that encourage behavior through market signals rather than through explicit directives. (HoSW 97) An environmental market-based approach uses markets, prices, and other economic variables to provide incentives for polluters to reduce or eliminate emissions. There are three types of market-based instruments on environmental policy:

- A price-based instrument: it alters the prices of goods and services to reflect their relative impact. For instance, by using taxes, introducing levies or providing subsidies to reduce emissions.
- A rights-based instrument: it controls the quantity of the environmental good or service to the socially desired level. For instance, by introducing a cap-and-trade scheme or offset scheme to achieve an emission reduction goal. And
- An instrument designed to reduce market friction: it aims to stimulate a market to produce a desired environmental outcome through improving the workings of existing markets by reducing transaction costs or improving information flows. For instance, substantial gains can be made in environmental protection by removing existing explicit or implicit barriers to market activity.

These instrument types and their applications are shown in Figure 1.1.

Compared with the regulatory instrument, the market-based instrument has its notable advantages on achieving the climate goal. First, such an MBI instrument is more cost effective than the CAC approach. In theory, if designed and implemented properly, the market-based instrument can achieve the emission reduction targets most cheaply and equalize the incremental amount that emitters spend to reduce pollution, rather than equalizing pollution levels among all emitters. The spend of these emitters is also called the marginal abatement cost. Second, the market-based instrument offers dynamic incentives for technology innovation. By applying the MBIs, powerful incentives can be provided

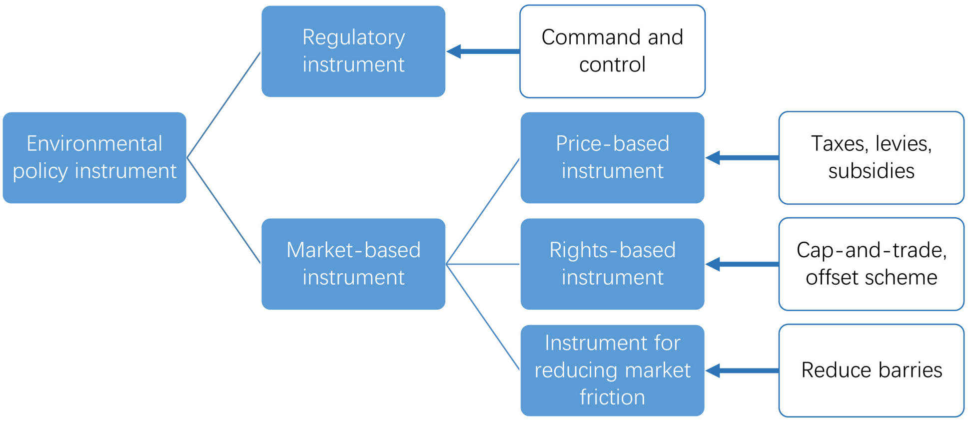


Figure 1.1: Types of environmental policy instruments and their applications

for companies to adopt cheaper and better technologies to reduce their emissions or even use clean technologies to avoid emissions. For more theoretical analysis on the advantages of MBIs, see for example: (OaPM 89), (DowW 86), and (JuKB 96). Studies on the characteristics and comparison of these instruments can be read in (BauO 88), (Tiet 95).

This thesis mainly focuses on the cap-and-trade system, i.e. the emission trading scheme, as it is nowadays widely applied over the globe and has become the most popular approach used by the policy makers to their environmental policy. Under a cap-and-trade principle, a cap will be set on the total amount of greenhouse gases that can be emitted by installations or companies covered by the system. Within the cap, companies with allocated or purchased tradable permits can sell or buy them to each other. At the end of each trading period, any company who does not have sufficient permits to cover its total emissions must face a penalty. The limit on the total number of tradable permits ensures that they have a value, and these permits can be traded as a commodity.

As an early example, the first launch of an emission trading system is in the USA. In 1995, a sulfur dioxide (SO2) emission trading system under the framework of the Acid Rain Program of the 1990 Clean Air Act in the U.S. is established. The European Union Emission Trading Scheme (EU ETS) is the world's first multinational cap-and-trade system for greenhouse gases. It is launched in 2005 and remains the world's biggest emission trading system.

As of 2016, it covers more than 11,000 heavy energy-using installations in all 28 EU countries plus Iceland, Liechtenstein and Norway. The system is now responsible for around 45% of the EU's greenhouse gas emissions. In 2008, the Chinese government announced to establish the Chinese emission trading scheme as part of its strategy to create a low carbon civilization. From 2013 to 2015, 7 pilot emission trading schemes were launched in different provinces and cities in China as a part of China's 12th Five-Year Plan which ran from 2011 to 2015. A national ETS is planned to be established in 2017 during the China's 13th Five-Year Plan which runs from 2016 to 2020. With the establishment of the Chinese national ETS, it will be potentially the world's largest emission trading system, which will cover around 50% of total domestic emissions. Meanwhile, other developed and developing countries have already or are planning to set their domestic and reginal emission trading systems. Some of them are discussing to link their trading systems together. When using the emission trading schemes, the carbon price, i.e. the price must be paid for the right to emit one tonne of CO2 into the atmosphere, is the key factor for a functional and operational system, and therefore will be the main research objective in this thesis.

1.2 Motivation of the Thesis

The motivation of this thesis consists of two separate parts. First, pricing of emission allowances and its relating derivatives plays significant role in the emission trading systems. Different pricing models for allowance price have been developed in recent years, only a few are useful on determining its corresponding derivatives. To price options on emission certificates, reduced-form models are proved to be useful. The aim of the thesis is to develop an option pricing model, which captures more market information. To achieve this goal, it is necessary to investigate a reduced-form model as the first step, then an extended pricing model will be developed based on the reduced-form model to extract information on the market price of risk and evaluate its impact on option prices of carbon permits.

Second, linking two emission trading systems on a global scale has become a more important issue. This has been discussed by many key market players (e.g. Europe-Switzerland, China- other Asian countries, China-Europe) and could be realized any time in an international momentum on reducing the global greenhouse gas emissions, especially after the 21st Conference of Parties (COP 21) in 2015, in which the Paris Agreement is adopted. The aim of this thesis is to investigate the price behavior under the linking mechanism. Using a static equilibrium model, it is possible to show that prices of emission permits in different trading schemes, either under a unilateral or a bilateral condition, will converge to a single price.

In order to solve the two problems mentioned above, it is necessary to understand the background and mechanism of the carbon market as the first step. The regulatory framework of international carbon market will be introduced first in this thesis, then the European Union Emission Trading Scheme (EU ETS). The background of international linking systems and their status will be specified as well.

1.3 Contribution and Structure of the Thesis

This thesis provides the following contributions:

1 Analysis of important international climate agreements of UNFCCC, including Kyoto Protocol and Paris Agreement:

  a) Illustrate how the carbon market mechanism of Kyoto Protocol looks like and what changes in the post-Kyoto period.
  b) Analyze the Paris Agreement and its possible impact on the climate change after 2020.
  c) Compare both Kyoto Protocol and Paris Agreement and show how they related to each other.

2 Analysis of EU ETS mechanism and the reform of EU ETS in the current and subsequent trading phases:

   a) Introduce how the basic mechanism of EU ETS looks like and illustrate how the system could be functional for trading emissions and achieving the emission reduction target.
   b) Analyze the reform of EU ETS and its impact on the on-going and subsequent trading phases.

3 Analysis of the carbon allowance price dynamics in a risk neutral framework:

   a) Explain the EUA futures price behavior theoretically.
   b) Develop a new stochastic model to capture more market information.
   c) Test both the original model and the new developed model and discuss their results.
   d) Apply the new model to price EUA options.
   e) Discuss carbon permit pricing methods by modelling the cumulative emission process.

4 Analysis of carbon linking systems on an international scale:

   a) Introduce the background of international carbon markets and their outlook.
   b) Discuss the possibility of international linking system of emission trading markets.
   c) Conduct equilibrium analysis on linking systems under different market settings.

This thesis is organized as follows: Chapter 1 is the introduction, which provides background, motivation and contribution of the thesis. Chapter 2 begins with the international regulatory framework on climate change and the most important decisions on stabilizing the greenhouse gas emissions. Two major milestones in the 21-year history of the global climate negotiations were made: The Kyoto Protocol in 1997 placed a limit on emissions to developed countries and the Paris Agreement in 2015 set out a roadmap in post-2020 to keep the world's temperature increase under a certain level. A market-based mechanism of emission trading is used to achieve the objective of these deals. Its impact will be analyzed. To act in concert with the international agreements, the European Union established its own system, known as the European Union Emission

Trading Scheme (EU ETS), to reduce the greenhouse gas emissions for all 28 European nations plus 3 other countries. Chapter 3 introduces the mechanism of the EU ETS, its trading assets and the price behavior of carbon permits. It specifies the current problems of the system and its reforms. In Chapter 4, price behavior of the carbon permits of EU ETS will be analyzed quantitatively. A reduced-form univariate price model will be introduced and will be extended into a bivariate model in order to capture more market information. Once the forwards price is determined, its related option price will be derived as well. The international background of linking system will be introduced in Chapter 5 and a static equilibrium model of linking system will be investigated to illustrate the price behavior in such a system. Finally, key findings of this thesis and their outlooks will be summarized in Chapter 6. Figure 1.2 shows the structure of the thesis.

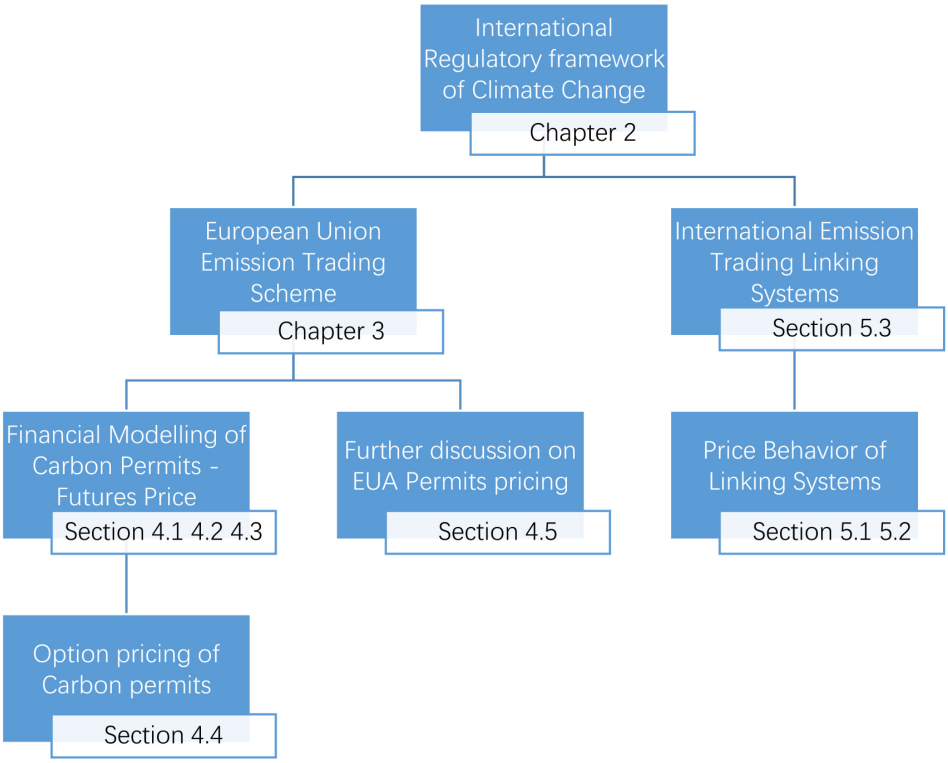


Figure 1.2: Structure of the thesis

2

Regulatory Framework

2.1 International Agreement on Climate Change

2.1.1 UNFCCC and IPCC

The effects of global climate change and global warming are becoming more and more evident. Scientists believe that they are already causing more frequent occurrences of extreme events such as drought, flooding and rises in malaria. Other phenomena attributed to climate change are increased incidents of hurricanes and forest fires. For the long-term impact, sea levels are rising, which could cause damage to crops and lead to wide-spread famine.

Nowadays, it is widely known that global warming is caused by an excess of heat-trapping gases, first and foremost carbon dioxide, methane and nitrous oxides. These gases mainly result from the burning of fossil fuels, from industries and agriculture. The gases prevent the sun's energy from radiating back into space after it has reached the surface of the Earth, much like the glass of a greenhouse. Therefore, how to control greenhouse gas concentrations in the atmosphere has become the key issue in this century.

The UNFCCC, known as the United Nations Framework Convention on Climate Change, is an international environmental treaty negotiated at the Earth Summit in Rio de Janeiro in June 1992, then entered into force in 1994. As the first international agreement on this issue, its objective is to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (UN 92). The UNFCCC came into force on 21 March 1994, after having been ratified by 192 nations. As of November 2016, there are 197 Parties, which include 196 States and 1 regional economic integration organization, to the United Nations Framework Convention on Climate Change (UNFCCC).

The UNFCCC is also the name of the United Nations Secretariat charged with supporting the operation of the Convention. That means, the work under the UNFCCC is facilitated by the secretariat, with its office in Bonn, Germany. And it is headed by the Executive Secretary. The Secretariat, augmented through the parallel efforts of the Intergovernmental Panel on Climate Change (IPCC), aims to gain consensus through meetings and the discussion of various climate strategies.

The Intergovernmental Panel on Climate Change (IPCC) is an intergovernmental organization for the assessment of climate change. It was established in 1988 by two United Nations organizations, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) and was endorsed by the United Nations General Assembly in the same year. The main task for IPCC is to provide the world with an objective, scientific view of climate change and its political and economic impacts. Currently, IPCC contains 195 countries as members, most of them are also members of UNFCCC.

The IPCC does not conduct its own original research on climate change, nor does it do the work of monitoring climate or related phenomena itself. The IPCC bases its assessment on the published literature, which includes peer-reviewed and non-peer-reviewed sources. That means, thousands of scientists from all over the world contribute to the work of the IPCC. The IPCC reviews the works to ensure an objective and complete assessment of current information can be provided to reflect a range of views and expertise on the issue of climate change.

The reports of IPCC cover "the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation", which is also known as the Principles governing IPCC work (IPCC 06).

So far, the IPCC has published five comprehensive assessment reports (AR) reviewing the latest climate science and the impacts of climate change. The first assessment report is published in 1990 with a supplementary report in 1992, a second assessment report (SAR) in 1995, a third assessment report (TAR) in 2001, a fourth assessment report (AR4) in 2007 and a fifth assessment report (AR5) in 2014. Currently, the IPCC is in its sixth assessment cycle and the Panel will produce the Sixth Assessment Report (AR6) and a series of special reports. The 43rd Session of the IPCC held in April 2016 agreed that the AR6 Synthesis Report would be finalized in 2022. Each of the Assessment Reports played a key role in informing decision makers as they shape climate policies over the next several years, especially for the Kyoto Protocol in 1997 and the Paris Agreement in 2015.

2.1.2 History of COP and its achievements

The United Nations Climate Change Conferences are yearly conferences held in the framework of the United Nations Framework Convention on Climate Change (UNFCCC). They serve as the formal meeting of the UNFCCC Parties. The Parties to the Convention have to meet annually from 1995 in the Conferences of the Parties (COP) to assess progress in dealing with climate change. The UNFCCC sets no binding limits on greenhouse gas emissions for individual nations and contains no enforcement mechanisms itself. Instead, the framework outlines how specific international treaties, usually called "Protocols" or "Agreements", can be negotiated to set binding limits on greenhouse gas emissions. The first binding agreement adopted by the COP is the well-known Kyoto Protocol during the COP 3 in 1997. From 2005 the Conferences also served as the Meetings of Parties of the Kyoto Protocol (CMP), so that Parties to the Convention that are not Parties to the Protocol can participate in Protocol-related meetings as observers. As of 2016, there are four states which are not Parties to the Protocol: Andorra, Palestine, South Sudan and Holy See. They served as observers to the CMP, but without the right to take decisions.

In the history of COP, progress has been made step by step on stabilizing the global warming problem. The first Conferences of the Parties (COP 1) was held in 1995 in Berlin. Parties agreed that the commitments in the Convention were “inadequate” for meeting the Convention’s objective. In a decision of COP, it agreed to establish a process to negotiate strengthened commitments for developed countries.

COP 3 took place in December 1997 in Kyoto, Japan. After intensive negotiations, delegates to COP agreed to a protocol to the UNFCCC that committed industrialized countries and countries in transition to a market economy to achieve legally binding targets on emission reduction. The Kyoto Protocol was adopted thereafter. These countries agreed to reduce their overall emissions of six GHGs by an average of 5% below 1990 levels in 2008-2012 with specific targets varying from country to country. Finally, the Kyoto Protocol entered into force on 16 February 2005 and now has 192 Parties.

The 11th COP held in 2005 in Montreal. The COP 11, also known as the first session of the CMP, established the Ad-Hoc Working Group on Annex I Parties’ further commitments under the Kyoto Protocol in accordance with Protocol Article 3.9, which mandated consideration of Annex I Parties’ further commitments at least seven years before the end of the first commitment period.

In COP 13 in 2007, a Bali Action Plan was adopted with aim to set a timeline and structured negotiation on the post-2012 framework, i.e. the post Kyoto Protocol period. It also established the Ad-Hoc Working Group on Long-term Cooperative Action under the Convention, with a mandate to focus on mitigation, adaptation, finance, technology, capacity building and a shared vision for long-term cooperative action.

COP 15 took place in Copenhagen in 2009. The overall goal of the conference was to establish an ambitious global climate agreement for the period from 2012 when the first commitment period under the Kyoto Protocol (2008-2012) expires. However, the conference did not achieve a binding agreement for long-term action, only a ‘political accord’ was negotiated by some key players such as China and USA, and was only ‘noted’ by the COP as it is considered an external document and would be discussed in the next conference.

One year later in COP 16, the Cancun Agreements was adopted on establishing several new institutions and processes. Also the Green Climate Fund (GCF) was created and designated as an operating entity of the Convention's financial mechanism. And Parties agreed to consider the adequacy of the global long-term goal during a 2013-2015 review.

At COP 17, the Durban outcomes covered a wide range of topics, notably a decision on long-term cooperative action under the Convention and agreement on the operationalization of the Green Climate Fund (GCF). Parties also decided to adopt an universal climate agreement no later than 2015, with work beginning under a new group called the Ad-Hoc working Group on the Durban Platform for Enhanced Action (ADP). The new instrument was plan to enter into force in 2020.

In 2014 at the COP 20, the Lima Conference was able to lay the groundwork for Paris by capturing progress made in elaborating the elements of a draft negotiating text for the 2015 agreement and adopting a decision on Intended Nationally Determined Contributions (INDCs). It also adopted the Lima Call for Climate Action, which sets in motion the negotiations towards a 2015 agreement in Paris.

The next Conference in 2015, COP21/CMP11, was held in Paris in December 2015 and resulted in adoption of the Paris Agreement, which governs climate change reduction measures from 2020. The Paris Agreement was opened for signature and then entered into force in November 2016 after some certain ratification conditions were satisfied. The adoption of this agreement ended automatically the work of the Durban platform, established during COP17.

The latest conference COP 22 was held in November 2016 in Marrakech, Morocco. During COP 22, Parties discussed the articles of the Paris Agreement in more details.

Table 2.1 summaries the pathway of COP and its main achievements in the history.

COP	Year	Place	Achievement
COP 1	1995	Berlin, Germany	Parties voiced concerns about the adequacy of countries' abilities to meet commitments.
COP 2	1996	Geneva, Switzerland	It accepted the scientific findings on climate change proffered by the IPCC in its second assessment and called for legally binding mid-term targets.
COP 3	1997	Kyoto, Japan	The Kyoto Protocol was adopted with legally binding targets on climate change.
COP 4	1998	Buenos Aires, Argentina	Parties adopted a 2-year Plan of Action to advance efforts and to devise mechanisms for implementing the Kyoto Protocol.
COP 5	1999	Bonn, Germany	It was a meeting with focus on the technical issues of the Kyoto Protocol. No major conclusions were made.
COP 6	2000	The Hague, Netherlands	Discussions of this COP evolved rapidly into a high-level negotiation over the major political issues, but did not reach a consensus.
COP 6	2001	Bonn, Germany	As the second part of COP 6, Bonn Agreement was reached with consensus on several issues, notably the mechanisms land-use change and forestry (LULUCF) and compliance.
COP 7	2001	Marrakech, Morocco	Marrakech Accords was made and included operational rules for international emissions trading among Parties to the Protocol and for the CDM and joint implementation.
COP 8	2002	New Delhi, India	The Delhi Ministerial Declaration was adopted, calling for efforts by developed countries to transfer technology and minimize the impact of climate change on developing countries.
COP 9	2003	Milan, Italy	It adopted decisions focus on the institutions and procedures of the Kyoto Protocol and on the implementation of the UNFCCC.

COP	Year	Place	Achievement
COP 10	2004	Buenos Aries, Argentina	The Buenos Aires Plan of Action was adopted to promote developing countries better adapt to climate change.
COP 11/ CMP 1	2005	Montreal, Canada	The Ad-Hoc Working Group on Annex I Parties' further commitments under the Kyoto Protocol was established.
COP 12/ CMP 2	2006	Nairobi, Kenya	Decisions were adopted at COP 12 designed to mitigate climate change and help countries adapt to the effects.
COP 13/ CMP 3	2007	Bali, Indonesia	The Bali Action Plan, roadmap on long-term issues of climate change, was adopted and the Ad-Hoc Working Group on Long-term Cooperative Action under the Convention was established.
COP 14/ CMP 4	2008	Pozna, Poland	It launched the Adaptation Fund under the Kyoto Protocol to help the poorest nations cope with the effects of climate change.
COP 15/ CMP 5	2009	Copenhagen, Denmark	The Copenhagen Accord, which included agreement on the long-term goal of limiting the global temperature increase, was noted by the Parties.
COP 16/ CMP 6	2010	Cancn, Mexico	Parties recognized the IPCC Fourth Assessment Report goal of a maximum 2 °C global warming and all Parties should take urgent action to meet this goal. The Cancn Agreement on creating Green Climate Fund and new institutions and processes was adopted.
COP 17/ CMP 7	2011	Durban, South Africa	The Ad-Hoc working Group on the Durban Platform for Enhanced Action was decided on achieving a universal climate agreement no later than 2015.

COP	Year	Place	Achievement
COP 18/ CMP 8	2012	Doha, Qatar	The COP 18 resulted in a package of decisions, referred to as the "Doha Climate Gateway", which included amendments to the Kyoto Protocol to establish its second commitment period (2013-2020)
COP 19/ CMP 9	2013	Warsaw, Poland	The meeting adopted an ADP decision that it invites Parties to initiate or intensify domestic preparations for their intended nationally determined contributions (INDCs).
COP 20/ CMP 10	2014	Lima, Peru	Groundwork for COP 21 by capturing progress was made.
COP 21/ CMP 11	2015	Paris, France	The Paris Agreement was adopted and muss wait for signature and ratification to enter into force.
COP 22/ CMP 12	2016	Marrakech, Morocco	More details on implementation of the Paris Agreement were discussed.

Table 2.1: History of COP and its main achievements

2.2 Kyoto Protocol

2.2.1 Essential background

The United Nations Framework Convention on Climate Change (UNFCCC) is the first international agreement on global climate change issues. However, this framework sets no binding targets on greenhouse gas emissions for its participants. The first international agreement with a binding target on the reduction of GHG emissions is the Kyoto Protocol (UN 98). In 1996, the IPCC published its Second Assessment Report (SAR) with additional special materials on the implications of various potential emission limitations and regional consequences, which provided key input to the negotiations that led to the adoption of the Kyoto Protocol to the UNFCCC. On 11 December 1997, after intensive negotiations, the Kyoto Protocol was adopted at COP 3 in Kyoto, Japan. On 16 February 2005, the Protocol entered into force. So far, there are 192 Parties to the Protocol, except for Canada.

Having the same objective as the UNFCCC, the Kyoto Protocol aimed to stabilize the concentration of greenhouse gases in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, just as specified in the Article 2 of UNFCCC. The principle of the protocol is based on common but differentiated responsibilities. That means, it puts the obligation to reduce current emissions on developed countries on the basis that they are historically responsible for the current levels of greenhouse gases in the atmosphere. The developing countries are not required to do so, and are only encouraged to reduce their emissions on a voluntary basis.

2.2.2 Participants

The UNFCCC divides countries into three main groups according to differing commitments. These are Annex I countries, Annex II countries and Non-Annex I countries.

Annex I countries consist of the industrialized countries that are members of the Organization for Economic Co-operation and Development (OECD) in 1992, plus countries with economies in transition (EIT), including the Russian Federation, the Baltic States, and several Central and Eastern European States.

Annex II countries include the OECD members of Annex I, but not the EIT Parties. These countries usually have to provide financial resources for developing countries to undertake emissions reduction activities under the Convention and to help them adapt to adverse effects of climate change.

Non-Annex I countries are mostly developing countries. Most of these countries belonged in the low-income group, with very few classified as middle-income. Others are the emerging economics, the wealthy Gulf and South Korea.

Under the Kyoto Protocol, only the Annex I Parties committed themselves to national or joint reduction targets. Formally this was called “quantified emission limitation and reduction objectives”. Non-Annex countries did not have binding targets. These countries did not commit themselves to any emission reduction target but still had to ratify the agreement so that the Kyoto Protocol could be agreed between the Annex I and Annex II Parties in order to allow the Annex I Parties to achieve their commitments partially by applying CDM projects, which will be introduced later. Table 2.2 shows the Annex I countries.

Annex I countries to UNFCCC (EIT countries are with $\star$)			
Australia	European Union	Liechtenstein	Russian Federation $\star$
Austria	Finland	Lithuania $\star$	Slovakia
Belarus $\star$	France	Luxembourg	Slovenia $\star$
Belgium	Germany	Malta	Spain
Bulgaria $\star$	Greece	Monaco	Sweden
Canada	Hungary	Netherlands	Switzerland
Croatia $\star$	Iceland	New Zealand	Turkey
Cyprus	Ireland	Norway	Ukraine $\star$
Czech Republic	Italy	Poland	UK
Denmark	Japan	Portugal	USA
Estonia $\star$	Latvia $\star$	Romania $\star$	

Table 2.2: Annex I countries to Kyoto Protocol - Source: UNFCCC

All non-Annex I countries can be seen in Table 2.3.

Non-Annex I countries to UNFCCC			
Afghanistan	Djibouti	Malawi	Sao Tome and Principe
Albania	Dominica	Malaysia	Saudi Arabia
Algeria	Dominican Republic	Maldives	Senegal
Andorra	Ecuador	Mali	Serbia
Angola	Egypt	Marshall Islands	Seychelles
Antigua and Barbuda	El Salvador	Mauritania	Sierra Leone
Argentina	Equatorial Guinea	Mauritius	Singapore
Armenia	Eritrea	Mexico	Solomon Islands
Azerbaijan	Ethiopia	Micronesia	Somalia
Bahamas	Fiji	Mongolia	South Africa
Bahrain	Gabon	Montenegro	South Sudan
Bangladesh	Gambia	Morocco	Sri Lanka
Barbados	Georgia	Mozambique	Sudan

Non-Annex I countries to UNFCCC			
Belize	Ghana	Myanmar	Suriname
Benin	Grenada	Namibia	Swaziland
Bhutan	Guatemala	Nauru	Syrian Arab Republic
Bolivia	Guinea	Nepal	Tajikistan
Bosnia and Herzegovina	Guinea-Bissau	Nicaragua	Thailand
Botswana	Guyana	Niger	The former Yugoslav Republic of Macedonia
Brazil	Haiti	Nigeria	Timor-Leste
Brunei Darussalam	Honduras	Niue	Togo
Burkina Faso	India	Oman	Tonga
Burundi	Indonesia	Pakistan	Trinidad and Tobago
Cambodia	Iran	Palau	Tunisia
Cabo Verde	Iraq	Palestine	Turkmenistan
Cameroon	Israel	Panama	Tuvalu
Central	African Republic Jamaica	Papua New Guinea	Uganda
Chad	Jordan	Paraguay	United Arab Emirates
Chile	Kazakhstan	Peru	United Republic of Tanzania
China	Kenya	Philippines	Uruguay
Colombia	Kiribati	Qatar	Uzbekistan
Comoros	Kuwait	Republic of Korea	Vanuatu
Congo	Kyrgyzstan	Republic of Moldova	Venezuela
Cook Islands	Lao People's Democratic Republic	Rwanda	Viet Nam
Costa Rica	Lebanon	Saint Kitts and Nevis	Yemen
Cuba	Lesotho	Saint Lucia	Zambia
Côte d'Ivoire	Liberia	Saint Vincent and the Grenadines	Zimbabwe
Democratic People's Republic of Korea	Libya	Samoa	

Non-Annex I countries to UNFCCC		
Democratic Republic of the Congo	Madagascar	San Marino

Table 2.3: Non-Annex I countries to Kyoto Protocol - Source: UNFCCC

2.2.3 Target of Kyoto Protocol

Objective of the Kyoto Protocol is to reduce the greenhouse gas emissions in the atmosphere. Greenhouse gases are defined by UNFCCC as gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds. This property causes the greenhouse effect. The targets of the Kyoto Protocol covered emissions of the six main greenhouse gases, namely:

- Carbon dioxide (CO2);
- Methane (CH4);
- Nitrous oxide (N2O);
- Hydrofluorocarbons (HFCs);
- Perfluorocarbons (PFCs); and
- Sulphur hexafluoride (SF6).

Among these, carbon dioxide (CO2), nitrous oxide (N2O), and methane (CH4) are the primary greenhouse gases in the Earth's atmosphere. Sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs) are other greenhouse gases which have far greater global warming potential but are much less prevalent. All of the six GHG are translated into CO2 equivalents in determining reductions in emissions. CO2-equivalent emission is a common scale for comparing emissions of different GHGs, they are weighted by Global Warming Potentials (GWP) with a 100-year time horizon. Table 2.4 below shows the lifetimes and direct 100-year GWP relative to CO2 for ozone-depleting substances and their replacements. These values are from the Intergovernmental Panel on Climate Change (IPCC), Second Assessment Report (SAR) (IPCC 95) and Fourth Assessment Report (AR4) (IPCC 07), respectively.

Greenhouse Gases	Formula	100yr GWP (SAR)	100yr GWP (AR4)
Carbon dioxide	CO2	1	1
Methane	CH4	21	25
Nitrous oxide	N2O	310	298
Hydrofluorocarbons	HFCs	140-11700	124-14800
Perfluorocarbons	PFCs	6500-9200	7390-13300
Sulphur hexafluoride	SF6	23900	22800

Table 2.4: Greenhouse gas emissions and their Global Warming Potentials - Data source: IPCC, SAR, AR4.

Under the Kyoto Protocol, all Annex I Parties are obligated to reduce their collective annual GHG emissions by 5.2% in average, compared to the baseline 1990 from 2008 to 2012. This period is defined as the first commitment period. For each Party, the assigned amount is known as the maximum amount of emissions, measured as the equivalent in carbon dioxide, that a Party may emit over a commitment period in order to comply with its emissions target. The individual targets for Annex I Parties are listed in the following Table 2.5.

Parties	Targets with baseline 1990
EU-15, Bulgaria, Czech Republic, Estonia, Latvia, Liechtenstein, Lithuania, Monaco, Romania, Slovakia, Slovenia, Switzerland	-8%
US	-7%
Canada, Hungary, Japan, Poland	-6%
Croatia	-5%
New Zealand, Russian Federation, Ukraine	0
Norway	1%
Australia	8%
Iceland	10%

Table 2.5: Individual targets for Annex I Parties to KP, 2008-2012 - Data source: Kyoto Protocol.

Baseline 1990 is defined as the base year for the national GHG inventory and the calculation of the assigned amount for most Parties. However, five Parties: Bulgaria, Hungary, Poland, Romania and Slovenia, have an alternative base year (UNFCCC 08). The base year for each of these Parties is as follows:

- Bulgaria: 1988;
- Hungary: the average of the years from 1985 to 1987;
- Poland: 1988;
- Romania: 1989; and
- Slovenia: 1986.

For these Parties, their assigned amounts should be calculated using the Annex A emissions in their specified base year or period, rather than 1990. An Assigned Amount Unit (AAU) is a tradable 'Kyoto unit' or 'carbon credit' representing an allowance to emit greenhouse gases comprising one metric tonne of carbon dioxide equivalents calculated using their Global Warming Potential (GWP). Assigned Amount Units are issued up to the level of initial "assigned amount" of an Annex I countries to the Kyoto Protocol. In this sense, the "assigned amounts" are the Kyoto Protocol Annex B emission targets, or say "quantified emission limitation and reduction objectives", expressed as levels of allowed emissions over the 2008-2012 commitment period. Table 2.6 below shows the initial assigned amount of Annex I countries published by the UNFCCC secretariat in 2008. Note that Belarus, Cyprus, Malta and Turkey are listed in the Convention's Annex I, but they do not have emission reduction targets in the Kyoto Protocol as they were not Annex I Parties when the Protocol was adopted.

The EU-15 includes Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherland, Portugal, Spain, Sweden, and UK. The 15 States who were EU members in 1997 when the Kyoto Protocol was adopted, took an overall target at -8% that must be redistributed among themselves. These countries have different individual targets, but which combined make an overall target for that group of countries. The EU reached an agreement on how its targets will be redistributed, which is called the Burden Sharing Agreement. The Burden Sharing Agreement entered into force in 1998, one year after the adoption of the Kyoto Protocol. The individual reduction

Parties	**Initial assigned amount**	**Parties**	**Initial assigned amount**
Australia	-	Liechtenstein	1,055,623
Austria	3,443,866,009	Lithuania	227,306,177
Belgium	673,995,528	Luxembourg	47,402,996
Bulgaria	610,045,827	Monaco	495,221
Canada	2,791,792,771	Netherlands	1,001,262,141
Croatia	-	New Zealand	309,564,733
Czech Republic	893,541,801	Norway	250,576,797
Denmark	276,838,955	Poland	2,648,181,038
Estonia	196,062,637	Portugal	381,937,527
European Community	19,621,381,509	Romania	1,279,835,099
Finland	355,017,545	Russian Federation	16,617,095,319
France	2,819,626,640	Slovakia	331,433,516
Germany	4,868,096,694	Slovenia	93,628,593
Greece	668,669,806	Spain	1,666,195,929
Hungary	542,366,600	Sweden	375,188,561
Iceland	18,523,847	Switzerland	242,838,402
Ireland	314,184,272	Ukraine	4,604,184,663
Italy	2,416,277,898	UK	3,412,080,630
Japan	5,928,257,666	US	-
Latvia	119,182,130		

Table 2.6: Initial assigned amount of Annex I Parties to Kyoto Protocol - Data source: UNFCCC secretariat. Data of US, Australia and Croatia are not published.

target for each EU-15 country over the first commitment period (2008-2012) is listed in Table 2.7.

EU-15 Parties	Individual target
Austria	-13%
Belgium	-7.50%
Denmark	-21%
Finland	0%
France	0%
Germany	-21%
Greece	25%
Ireland	13%
Italy	-6.50%
Luxembourg	-28%
Netherlands	-6%
Portugal	27%
Spain	15%
Sweden	4%
UK	-12.50%

Table 2.7: Individual reduction targets of EU to Kyoto Protocol, 2008-2012 - Data source: EEA.

Figure 2.1 shows the Burden Sharing target for each of the EU-15 countries and its corresponding annual reduction volume of GHG emissions.

Instead of reducing the GHG emissions, human activities such as afforestation and reforestation are also considered as an effective way to stabilize the climate change. Forests present a significant global carbon stock accumulated through growth of trees and an increase in soil carbon. Under the United Nations Framework Convention on Climate Change any process, activity or mechanism which removes a greenhouse gas from the atmosphere is referred to as a "sink" (UN 92). Human activities impact terrestrial sinks, through land use, land-use change and forestry (LULUCF) activities. LULUCF activities help to increase the removals of greenhouse gases from the atmosphere or decrease emissions by sources leading to an accumulation of carbon stocks. Therefore, Annex I countries are allowed to use a limited amount of permits resulting from

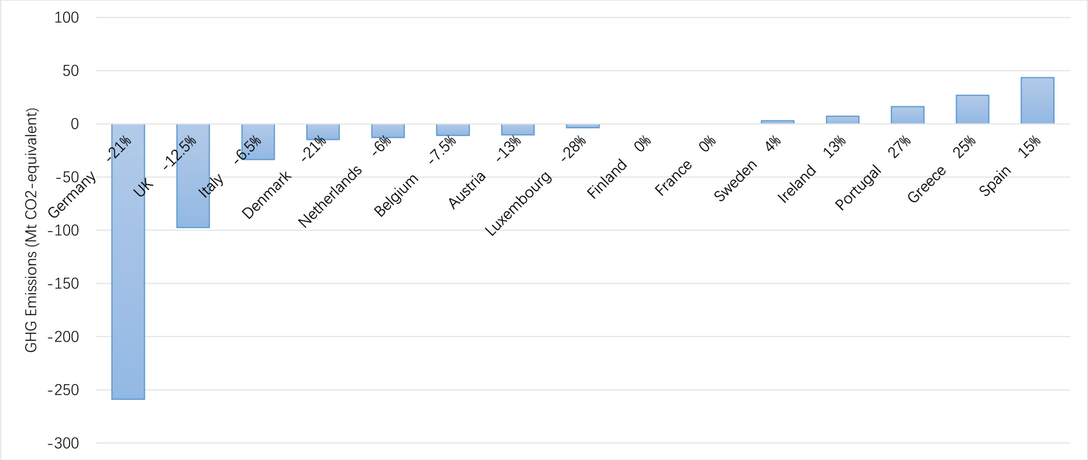


Figure 2.1: Burden Sharing targets for EU-15 countries to Kyoto Protocol

the LULUCF activities for their compliance.

2.2.4 Mechanism

Annex B countries with commitments under the Kyoto Protocol to limit or reduce greenhouse gas emissions must meet their targets primarily through national measures. However, to achieve the emission reduction target more efficiently, the Kyoto Protocol defines different market-based mechanisms for the Annex B countries to meet their individual emission limitation commitments as additional means. These Kyoto mechanisms are:

1. Emission Trading (ET)
2. Clean Development Mechanism (CDM)
3. Joint Implementation (JI)

Emission trading (ET) mechanism is a flexibility measure allows Annex B countries to trade their emission permits among themselves. The allowed emissions during the first commitment period of Kyoto are divided into assigned amount units (AAUs). Countries have sufficient emission units can sell this excess capacity to countries that are over their targets. Since the overall assigned amount units are limited for these countries and trading is allowed among them, the emission permits can be seen as a new commodity. Beside AAUs, other units can be traded or sold under the Kyoto Protocol's emissions trading scheme as well. These are: The Certified Emission Reductions (CERs) generated from the Clean Development Mechanism (CDM); The Emission Reduction Units (ERUs) generated by the Joint Implementation Mechanism (JI); And the Removal Units (RMUs) based on the land use, land-use change and forestry (LULUCF) activities. Table 2.8 summarizes the status of international emission trading systems of the Annex I countries to the Kyoto Protocol.

Both Clean Development Mechanism (CDM) and Joint Implementation (JI) are project-based mechanisms. The Clean Development Mechanism (CDM) allows a country to implement an emission-reduction project in developing countries. Once a project has been implemented successfully, a certain number of saleable Certified Emission Reduction (CER) credits, each equivalent to one tonne of CO2, can be used by this Annex B country to meet its Kyoto target. Being operational since 2006, this mechanism has already registered more than 1,650 projects and is anticipated to produce 2.9 billion CERs in the first commitment period of the Kyoto Protocol, most of them are created by the projects in China.

Similar to the Clean Development Mechanism (CDM), the Joint Implementation (JI) mechanism is also project-based but allows an Annex B country to earn emission reduction units (ERUs) from an emission-reduction or emission removal project in another Annex B country. The created units can be counted towards meeting its own Kyoto target. This means a project between two developed countries. The purpose of a JI project is to provide developed countries a flexible and cost-efficient way for fulfilling a part of their Kyoto commitments, while the host country can benefit from foreign investment and technology transfer.

2.2.5 Compliance

AAUs, CERs, ERUs and RMUs are tradable units under the Kyoto Protocol's emissions trading scheme. Their transfers and acquisitions have to be tracked and recorded through the registry systems under the Kyoto Protocol. Two types of registry are being implemented. First, national registries have been implemented by the governments of all 38 Annex B countries under the Kyoto

Country	**System**	**Start in**	**Scope**	**Reduction target**	**Sector**
Australia	GGAS	2003	New South Wales	7.27 tonnes of carbon dioxide per capita by the year 2007	Electricity retailer and certain other Parties including large electricity users
Canada	Alberta's ETS	2007	Alberta	50 million tCO2 e reduction by 2020	Industry, forestry, energy and waste
European Union	EU ETS	2005	EU, Norway, Iceland, and Liechtenstein	21% by 2020 compared to 2005	Power and heat generation, industry, aviation
Japan	Tokyo ETS	2010	Tokyo	25% by 2020 compared to 2000 levels	Large-scale facilities (buildings/factories) for industrial and commercial sector purpose
New Zealand	NZ ETS	2008	nation-wide	0% below 1990 levels during the first Kyoto period	Forestry, energy, industry and waste
Norway	Norwegian ETS	2005	nation-wide	less than 1% increase compared to 1990 levels during 2008-2012	Power and heat generation, industry
Switzerland	Swiss ETS	2008	nation-wide	20% by 2020 compared to 1990 levels	Cement, chemicals, refineries, paper, heat and steel
UK	UK ETS	2002	nation-wide	20% by 2010 compared to 1990 levels	Industries and organisations who promised to make reductions
US	RGGI	2009	10 north-eastern U.S. states	more than 45% by 2020 relative to 2005 levels	Fossil fuel Power Plants

Table 2.8: International Emission Trading Systems of Annex I Countries before 1. Kyoto Period

Protocol. These national registries contain accounts within which units are held in the name of the government or in the name of legal entities authorized by the government to hold and trade units. Second, the UNFCCC secretariat has implemented the CDM registry for issuing CDM credits and distributing them to national registries.

An international transaction log (ITL) ensures secure transfer of emission reduction units between countries. The international transaction log (ITL) is administrated by the UNFCCC secretariat, it verifies registry transactions in real time, to ensure they are consistent with rules agreed under the Kyoto Protocol. One of important function of the ITL is to support the review and compliance process of the Kyoto Protocol.

When trading the emission units, in order to make sure that all Annex B countries will not oversell their units and subsequently are not able to meet their own emissions targets, each country is obligated to maintain a reserve of AAUs, CERs, ERUs and EMUs in its national registries. This reserve is required not to drop below 90% of the country's assigned amount or 100% of five times its most recently reviewed inventory, whichever is lowest. This reserve is known as the Commitment Period Reserve (CPR).

According to Kyoto Protocol, all Annex I Parties are obligated to reduce their collective annual GHG emissions by 5.2% in average, compared to the baseline 1990 from 2008 to 2012. For a few countries, the base year is other than 1990. For each country, their individual reduction targets differ. The base year level of total national emissions will be calculated for each Annex B Party. This together with the corresponding individual reduction target determines the total assigned amount that will be distributed to the Parties for their use during the first Kyoto commitment period.

We take Austria as an example. Austria has the base year of 1990. It faces a reduction target of 13% under the Kyoto Protocol. The country has emitted in this year totally 79,049,657 tonnes CO2 equivalent. Therefore, the total number of initial assigned amount for this country during the first commitment period from 2008 to 2012 (5 years in total) is calculated by:

$$79,049,657 \text{ tCO2} \times 5 \times (100\% - 13\%) = 343,866,009 \text{ tCO2}.$$

This means Austria faces a cap of 68,773,202 tonnes CO2 equivalent annually in average from 2008 to 2012. Table 2.10 summarizes the emission reduction targets of all 38 Annex B countries under the Kyoto Protocol, their base year level of total national emissions in tCO2 and their initial assigned amounts in tCO2.

Annex B Party	Target	Base year	Base year level	IAA in tCO2
Australia	8%	1990	547,699,841	2,957,579,141
Austria	-13%	1990	79,049,657	343,866,009
Belarus	-	-	-	-
Belgium	-7.5%	1990	145,728,763	673,995,528
Bulgaria	-8%	1988	132,618,658	610,045,827
Canada	-6%	1990	593,998,462	2,791,792,771
Croatia	-5%	1990	31,321,790	148,778,503
Czech Republic	-8%	1990	194,248,218	893,541,801
Denmark	-21%	1990	69,978,070	276,838,955
Estonia	-8%	1990	42,622,312	196,062,637
European Union	-8%	1990	4,265,517,719	19,621,381,509
Finland	0%	1990	71,003,509	355,017,545
France	0%	1990	563,925,328	2,819,626,640
Germany	-21%	1990	1,232,429,543	4,868,096,694
Greece	25%	1990	106,987,169	668,669,806
Hungary	-6%	1985-87	115,397,149	542,366,600
Iceland	10%	1990	3,367,972	18,523,847
Ireland	13%	1990	55,607,836	314,184,272
Italy	-6.5%	1990	516,850,887	2,416,277,898
Japan	-6%	1990	1,261,331,418	5,928,257,666
Latvia	-8%	1990	25,909,159	119,182,130
Liechtenstein	-8%	1990	229,483	1,055,623
Lithuania	-8%	1990	49,414,386	227,306,177
Luxembourg	-28%	1990	13,167,499	47,402,996
Monaco	-8%	1990	107,658	495,221
Netherlands	-6%	1990	213,034,498	1,001,262,141
New Zealand	0%	1990	61,912,947	309,564,733
Norway	1%	1990	49,619,168	250,576,797
Poland	-6%	1988	563,442,774	2,648,181,038
Portugal	27%	1990	60,147,642	381,937,527
Romania	-8%	1989	278,225,022	1,279,835,099
Russian Federation	0%	1990	3,323,419,064	16,617,095,319

Country	System	Start in	Scope	Reduction target
Slovakia	-8%	1990	72,050,764	331,433,516
Slovenia	-8%	1986	20,354,042	93,628,593
Spain	15%	1990	289,773,205	1,666,195,929
Sweden	4%	1990	72,151,646	375,188,561
Switzerland	-8%	1990	52,790,957	242,838,402
Ukraine	0%	1990	920,836,933	4,604,184,663
UK	-12.5%	1990	779,904,144	3,412,080,630

Table 2.9: Annex B countries, their reduction targets, base year emissions and the corresponding Initial Assigned Amount of Kyoto Protocol

Since trading is allowed and different kinds of permit units can be transferred among Annex B Parties, these countries shall not only focus on their use of AAUs, but also on the other tradable units in their national registries for compliance. Therefore, in order to compliance, the total number of permit units in the national registry of one country is calculated as:

$$\begin{aligned}\text{Total number of permits in the national registry} &= \text{Initial Assigned Amount} \\ &+ \text{AAUs} + \text{CERs} + \text{ERUs} + \text{RMUs}.\end{aligned}$$

Note that the amount of AAUs, ERUs and RMUs can be also negative, which means more units of such permits are sold than bought by this country. The number of CERs can only be positive, since they can be only bought by an Annex B country from a CDM project established in a developing (Non-Annex I) country.

In implementation of Kyoto Protocol during the first commitment period, Annex B Parties face two situations at the end: compliance and non-compliance.

Compliance means a Party has sufficient number of permit units in its national registry to cover its total emissions between 2008 and 2012. Or say, the number of permits in the national registry must be no less than the number of tonnes emissions between 2008 to 2012. However, there is a special case with compliance: A Party can "over-achieve" its reduction target in the first commitment period by holding more permits in its national registry than its real emissions. Then this Party is allowed to bank its unused units for use in the subsequent period, if there is one. However, not all kinds of permits can be banked in total to the subsequent period. There are restrictions on the volume of RMUs, CERs and ERUs. RMUs cannot be banked for use in subsequent periods, but their volume is sufficiently small that they can readily be used in the first period for compliance. Similar remarks apply to ERUs and CERs, of which a maximum of 2.5% of Initial Assigned Amounts each can be banked. (Grub 03)

In case of non-compliance, a Party does not have sufficient permits to cover its real emissions, then it faces a penalty. This Party is then required to make up the difference between its real emissions and its assigned amount during the subsequent commitment period, plus an additional deduction of 30%. For example, if Country A fails to fulfill the compliance condition and has a lack of 100 million permits in the first commitment period, then it will receive 100 million permits less in the second commitment period than as planned. Moreover, it has to hand in 30 million additional permits during the second period. Recall that this penalty mechanism will be only functional if the second commitment period exits.

The Compliance Committee under the Kyoto Protocol is responsible for the compliance mechanism of Annex B Parties and is made up of two branches: the facilitative branch and the enforcement branch. The facilitative branch provides advice and assistance to Parties in order to promote compliance, whereas the enforcement branch has the responsibility to determine if an Annex B Party is not in compliance with its emissions targets. In the case of compliance with emission targets, if a Party's actual emissions exceed its assigned amount of Kyoto units for that commitment period, the Compliance Committee will give this Party 100 days to make up any shortfall in compliance by acquiring AAUs, CERs, ERUs or RMUs through emissions trading. If, at the end of this period, this Party's emissions are still greater than its assigned amount, the enforcement branch will declare the Party to be in non-compliance and apply.

2.2.6 Ratification of Kyoto Protocol

On 11 December 1997, the Kyoto Protocol was adopted by COP 3 and was opened for signature on 16 March 1998 during one year by Parties to UNFCCC.

Before the expiration of the signature period, 82 countries and the European Community signed the Protocol. For the Protocol to enter into force, it has to be ratified by the Parties. Singing indicates an intention to ratify the Protocol. Ratification means that a Party is legally bound by the provisions of the treaty. For Annex I Parties this means that it agrees to cap emissions in accordance with the Kyoto Protocol.

Article 25 of the Protocol specifies that the Protocol enters into force "on the ninetieth day after the date on which not less than 55 Parties to the Convention, incorporating Parties included in Annex I which accounted in total for at least 55% of the total carbon dioxide emissions for 1990 of the Annex I countries, have deposited their instruments of ratification, acceptance, approval or accession." (UN 98) The ratification process started on 17 September 1998. Once the Kyoto Protocol enters into force, it has the same legal effect to all Annex B countries.

Iceland was the 55th state to ratify the Protocol, that fulfilled the first condition for coming-into-force. With Russia's ratification on 18 November 2004, the "55 percent of 1990 carbon dioxide emissions of the Parties included in Annex I" clause was satisfied and the treaty was brought into force, effective 16 February 2005, after the required lapse of 90 days. So far, there are 192 Parties, including 191 States and 1 regional economic integration organization, to the Kyoto Protocol to the UNFCCC.

The USA, accounting for 36% of total global emissions in 1990, signed the Protocol on 12 November 1998, but did not submitted to the Senate for ratification during the Clinton presidency. The treaty has to become binding in the USA only if it has to be ratified by the Senate. However, a passed no-binding resolution by the Senate in July 1997, the Byrd Hagel Resolution, expressed that the US would not approve any international agreement that did not require developing countries to make emission reductions and would seriously harm the economy of the United States. Even in the presidency of George W. Bush, his administration's position was opposed the Kyoto treaty. As of 2016, the USA is the only signatory that has not ratified the Protocol.

In 2011, the Canadian government announced that Canada was legally withdrawing from the Protocol. According to the Protocol, Canada was committed to cutting its GHG emissions to 6% below 1990 levels by 2012. However, the country's total emissions in 2009 were 17% higher than its 1990's level. Therefore, Canada chose to withdraw because it calculated that it would have to pay approximately 14 billion Canadian dollars in buying emission permits from other Kyoto protocol countries to meet its commitment target. However, the country could have also chosen to not meet its target and be declared non-compliant. Then, under the enforcement procedure, its corresponding carbon deficit, plus an additional penalty deduction of 30% from its assigned amount, would have been carried over to the second commitment period. Therefore, in order to avoid enormous financial penalties, the Canadian government chose to withdrawal from the Protocol. Currently, Canada is the only country that withdraw from the Kyoto Protocol after the ratification.

2.2.7 Doha Amendment and second commitment period

The first commitment period of the Kyoto Protocol started in 2008 and ended on 31 December 2012. To ensure there is no gap between commitment periods, the Kyoto Protocol Parties agreed at Durban Conference in 2011 that a second commitment period shall begin on 1 January 2013. And this agreement was adopted in the Doha Conference in 2012, known as the Doha Amendment to the Kyoto Protocol. (UN 11)

The Doha Amendment set an eight-year-long commitment period, running from 1 January 2013 until 31 December 2020. Parties to the Kyoto Protocol of the second commitment period are required to reduce their aggregate emissions by 18% below the 1990 levels in average. The reduction commitment of each individual Parties range from 24% to 0.5%. The European Union, as a whole Party, is required to reduce its emissions by 20%. Table 2.10 shows the reduction commitments of the Parties to the second period, compared to their reduction commitments to the first Kyoto period.

There are totally 37 countries with binding targets: The European Union with its 28 member states, Australia, Belarus, Iceland, Kazakhstan, Liechten-

Annex B Party	KP target	Doha target
Australia	8.0%	-0.5%
Austria	-13.0%	-20.0%
Belarus	-	-12.0%
Belgium	-7.5%	-20.0%
Bulgaria	-8.0%	-20.0%
Croatia	-5.0%	-20.0%
Cyprus	-	-20.0%
Czech Republic	-8.0%	-20.0%
Denmark	-21.0%	-20.0%
Estonia	-8.0%	-20.0%
European Union	-8.0%	-20.0%
Finland	0.0%	-20.0%
France	0.0%	-20.0%
Germany	-21.0%	-20.0%
Greece	25.0%	-20.0%
Hungary	-6.0%	-20.0%
Iceland	10.0%	-20.0%
Ireland	13.0%	-20.0%
Italy	-6.5%	-20.0%
Kazakhstan	-	-5.0%
Latvia	-8.0%	-20.0%
Liechtenstein	-8.0%	-16.0%
Lithuania	-8.0%	-20.0%
Luxembourg	-28.0%	-20.0%
Malta	-	-20.0%
Monaco	-8.0%	-22.0%
Netherlands	-6.0%	-20.0%
Norway	1.0%	-16.0%
Poland	-6.0%	-20.0%
Portugal	27.0%	-20.0%
Romania	-8.0%	-20.0%
Slovakia	-8.0%	-20.0%
Slovenia	-8.0%	-20.0%
Spain	15.0%	-20.0%
Sweden	4.0%	-20.0%
Switzerland	-8.0%	-15.8%
Ukraine	0.0%	-24.0%
UK	-12.5%	-20.0%

Table 2.10: Reduction commitments of Kyoto Protocol and Doha Amendment - Data source: Doha Amendment, UNFCCC.

stein, Norway, Switzerland, and Ukraine. Belarus, Cyprus, Malta and Kazakhstan were not Annex B Parties of the Kyoto Protocol in the first commitment Period, but have their reduction commitments for the second period, as Belarus, Cyprus and Malta are listed in the Convention's Annex I list, but they do not have emission reduction targets in the Kyoto Protocol. Kazakhstan does not have a target, but has declared that it wishes to become an Annex I Party to the Convention in the first Kyoto period. However, after the adaptation of the Doha Amendment, Belarus, Kazakhstan and Ukraine stated that they may withdraw from the Protocol or not put into legal force the Amendment with second round targets. Japan, New Zealand and Russia have binding targets in the first Kyoto period but did not take any new targets in the second commitment period. Other developed countries without reduction targets for the second period are Canada and USA. Canada withdrew from the Kyoto Protocol in 2012 and USA did not ratify the Protocol.

According to the Kyoto Protocol, the Doha Amendment can only enter into force, when at least 144 Annex I countries to the UNFCCC have ratified it. However, as of November 2016, only 66 states have accepted the Doha amendment. This means the second commitment period of the Kyoto Protocol is still not binding under international law. Thereafter, all Annex B Parties would not be legally bound by their reduction commitments in respect of the period after 31 December 2012.

An absent of the entry into force of the Doha Amendment may cause problems for ensuring the Kyoto Protocol's operational continuity. For instance, the Kyoto Protocol requires that Annex B Parties have to review their reduction commitments by the end of 2014 with a view to increasing the level of their mitigation ambition. However, without a binding target, any commitment would not be forced and therefore cannot ensure the compliance. The market mechanism of the Kyoto Protocol also requires a continuity of the commitment periods to ensure compliance mechanism. In the first Kyoto Period, Annex B Parties may carry over their surplus permit units into the subsequent trading period. Meanwhile, Parties do not have sufficient permits to cover their total emissions will face a penalty and have to make up the difference between their real emissions and their assigned amount during the subsequent commitment period, plus an additional deduction of 30%. If the second commitment period is not legally binding, then the compliance mechanism would not be functional.

2.3 COP 21 and Paris Agreement

On 12 December 2015, the Paris Agreement was adopted at the 21st Conference of the Parties (COP 21) of the UNFCCC in Paris by 195 countries. The Paris Agreement is an international agreement within the UNFCCC dealing with greenhouse gases emissions and climate change issues. After the adaptation, it was opened for signature on 22 April 2016 and then entered into force on 4 November 2016, after sufficient states ratified the agreement and therefore the conditions for entering into force were satisfied.

2.3.1 Aims and NDCs

The Kyoto Protocol aims to stabilize the concentration of greenhouse gases in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. For this purpose, it puts the obligation to reduce emissions on developed countries, but without setting any target on the developing countries. Unlike the Kyoto Protocol, the Paris Agreement sets emission reduction target for all countries and regional economic integration organization. In this sense, it is also seen as the world's first comprehensive climate agreement. The aim of this deal is stated in Article 2 of the Paris Agreement (UN 15a):

- Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;
- Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production;
- Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.

The primary task of Paris Agreement is to hold the increase in global average temperature to well below 2°C, and to pursue efforts to limit the temperature increase to 1.5°C, as well as to achieve net zero emissions in the second half of this century. To achieve this long-term goal, the Nationally Determined Contributions (NDCs), described in Article 3 of the Agreement, are used as a bottom-up approach since the fully implementation of Paris Agreement. Generally, NDCs are the commitments of each country under UNFCCC on how they will cut emissions for the post-2020 period.

Before Cop 21 in December 2015, developed and developing countries submitted their national post-2020 climate action commitments to UNFCCC, known as Intended Nationally Determined Contributions (INDCs). The INDC of a country specifies the target of reductions in greenhouse gas emissions of this country. The word ‘intended’ was used because countries were communicating proposed climate actions before COP 21, in which the Paris Agreement was adopted. All INDCs submitted were included in a synthesis report by the UNFCCC secretariat in October 2015 and this report was updated in May 2016 (UN 15b) (UN 16). The report reflects the aggregate emissions impact of INDCs. After the adaptation of Paris Agreement, the INDC of a country became the first Nationally Determined Contribution (NDC) when it ratified the agreement, unless the country decided to submit a new NDC at the same time. After the Paris Agreement was ratified, the NDCs became the first greenhouse gas targets under the UNFCCC to all developed and developing countries. The status of NDCs are recorded in the NDC registry under UNFCCC and is regulated by the UNFCCC secretariat.

However, the current commitments on NDCs are not consistent with limiting global warming to well below 2°C, as stated in the Paris Agreement. This means the current NDCs are not the final targets to the deal. Therefore, the NDCs are designed to be assessed and improved regularly, so that they are able to achieve the global temperature reduction aim. This mechanism will be explained in the subsequent subsection.

2.3.2 Main features of Paris Agreement

The Paris Agreement covers the traditional thematic areas of the UNFCCC such as mitigation, adaptation, financing and other climate relative issues. The decisions on these key issues will be specified in this subsection.

Mitigation

Generally, mitigation means mitigating climate change by reducing GHG emissions from human activities. It corresponds with the ultimate objective of the UNFCCC, namely to stabilize GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Mitigating climate change consists of actions to limit the magnitude or rate of long-term climate change, and can also be achieved by increasing the capacity of carbon sinks, e.g., through reforestation, as stated by the IPCC's Fourth Assessment Report (IPCC 07).

Unlike the Kyoto Protocol, the Paris Agreement does not set any concrete emission reduction target to the Parties of UNFCCC. Instead, it sets objective of holding temperature well below 2°C while also pursuing efforts to stay below 1.5°C (Article 2(1)). The temperature target is then translated into emission reduction targets: to decline the global emissions as soon as possible and to realize a balance of net zero GHG emissions in the second half of the century (Article 4(1)). For this purpose, the NDC mechanism is implemented and has to be improved regularly (Article 4(2)). Moreover, the NDCs submitted by Parties will be recorded in a public registry by the secretariat of UNFCCC and not in the Agreement itself (Article 4(12)). As of November 2016, 111 Parties have submitted their first NDCs saved in the registry under `http://www4.unfccc.int/ndcregistry/Pages/All.aspx`.

However, Parties to UNFCCC are not obligated to fulfill their NDCS' plans. Developed countries should undertake the economy-wide absolute emission reduction targets. And developing countries are encouraged to move towards such targets (Article 4(4)). Also, the NDCs submitted by Parties are not on the same timeframe. Some of the current NDCs start in 2020, others in 2021. Most of them indicate an implementation timeline up to 2030, and some of them up to 2025. Some NDCs have multiyear targets, some have single year targets. Therefore, Parties are also encouraged to develop and communicate long-term low greenhouse gas emission strategies. The Agreement specifies that these NDCs should point towards 2050 as mid-century targets and invites all Parties to communicate their strategies by 2020 (Article 4(19)). As of November 2016, USA, Mexico, Germany and Canada submitted their long-term strategy to the secretariat of UNFCCC. Their long-term goals can be found here:`http://unfccc.int/focus/long-term_strategies/items/9971.php`.

Recognizing the current NDCs are not sufficient to achieve the temperature target on well below 2°C, the Paris Agreement also specifies the assessment and improvement of the NDCs. Parties to UNFCCC are required to regularly submit their national emissions inventories and report on their progress. Every five years, collective progress towards achieving the long-term goals of the Paris Agreement has to be assessed, and countries must submit their new NDCs representing greater action than their previous plans (Article 4(2)). Furthermore, each new NDC should be more ambitious than the previous one, known as the principle of progression (Article 4(3)). Also, an upward adjustment of NDCs is possible at any time (Article 4(11)).

Also in every five years, a global stocktake has to be made to assess the collective progress towards achieving the purpose of the Agreement and the long-term temperature goal (Article 14(1)). Each new NDC shall be informed by the outcome of the preceding stocktake. Therefore, the global stocktakes are scheduled to give Parties time to include the results in the preparation of their next NDC. The first stocktake will take place in 2023 (Article 14(2, 3)). And a facilitative dialogue will take stock of efforts in 2018 first. The assessment and improvement mechanism of NDCs together with the global stocktakes ensure that the long-term goal of the Paris Agreement can be achieved. Figure 2.2 illustrates how this NDC mechanism works.

Adaptation

Another major area of action under the UNFCCC is adapting to the adverse effects of climate change. adaptation refers to the actions that countries will need to take to respond to the impacts of climate change that are already happening, while at the same time preparing for future impacts. Unlike the mitigation,

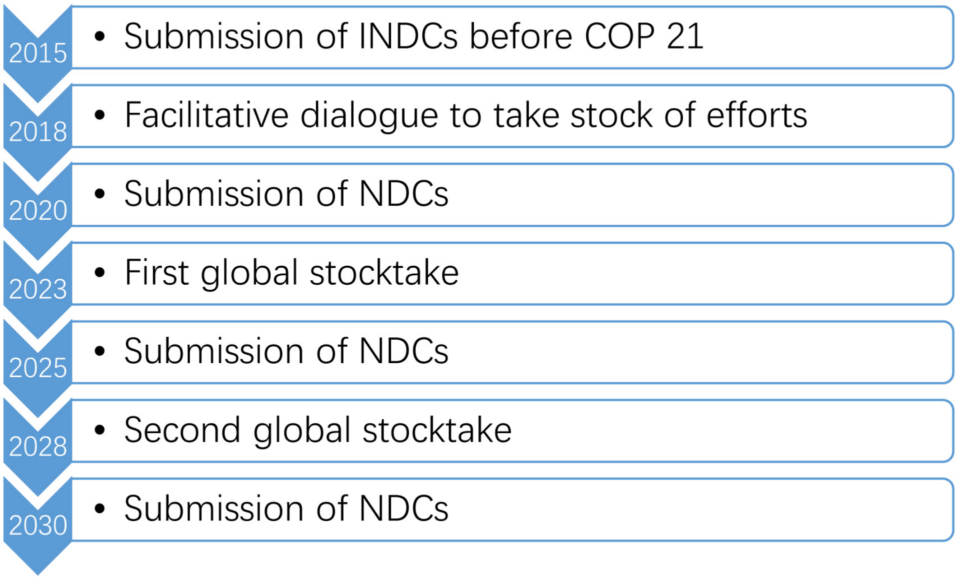


Figure 2.2: NDC and global stocktaking mechanism

provisions regarding adaptation for individual Party are less precise than those on mitigation.

The Paris Agreement sets a global goal to significantly strengthen national adaptation efforts, namely to enhance adaptive capacity, strengthen resilience and reduce vulnerability to climate change (Article 7(1)). For this purpose, all Parties should submit and update periodically an adaptation communication on their priorities, implementation and support needs, plans and actions (Article 7(10, 11)), and the submitted adaptation communications will be recorded in a public registry (Article 7(12)). It is worth to mention that provisions on adaptation are all qualitative and do not include any quantitative goal, this might reflect the difficult of prescribing specific actions for individual countries on an international level.

Climate finance

As the third key issue of the Paris Agreement, climate finance refers to local, national or transnational financing that seeks to support mitigation and adaptation actions that will address the climate change problem.

In accordance with the Agreement, developed countries shall provide financial resources to assist developing countries with respect to both mitigation and adaptation in continuation of their existing obligations under the UNFCCC (Article 9(1)). Other countries are encouraged to provide or continue to provide such support voluntarily (Article 9(2)). Apart from providing financial support, the Agreement also establishes that developed countries should continue to take the lead in the global effort to mobilize climate finance from a wide variety of sources (Article 9(3)).

Although there is no quantitative financing goal specified in the Paris Agreement, the expression on this issue together with the long-term goal on mitigation and adaptation is a major innovation. The statement making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development, send a strong signal to the private sector to reassess and redirect its investments, for instance, in the low carbon technologies or in the renewable energy.

2.3.3 Criticism and outlook

The Paris Agreement as an international deal on climate change entered into force by November 2016. However, it still has to be translated into domestic decisions in each country in order to realize emission reduction target in an effective way. The Agreement itself is seen as a binding international treaty, but some key issues in the document do not have binding enforcement mechanism. One of significant issues is the statement of Nationally Determined Contributions (NDCs).

The current NDC level is seen not sufficient to achieve the well below 2°C target. Therefore, countries are required to review their domestic NDCs every five years and they have to submit more ambitious plans. However, the statement of the NDC mechanism in the Agreement is not legally binding. Furthermore, there is also no mechanism to force countries to the UNFCCC to set a target in their NDC by a specific date and no enforcement if one countries fails to meet its NDC target. This could lead to the problem that countries could withdraw from the Agreement without bearing too much economic losses, since they will not be punished, just as what happened to Canada in the first commitment period of the Kyoto Protocol. Furthermore, even for some binding targets in the Agreement, there is no enforcement mechanism and no penalties if countries failed to meet them.

The Paris Agreement does not mention the carbon market as well, although it is considered as an important incentive for reducing the GHG emissions. Instead, it establishes three different types of international cooperation on mitigation and adaptation for increasing ambition (Article 6(1)). A cooperative approach allows Parties to engage bilaterally or multilaterally by using international transferred mitigation outcomes towards NDCs (Article 6(2)). A sustainable development mechanism involving both public and private entities, which may in some aspects be similar to the CDM of the Kyoto Protocol (Article 6(4)). And a non-market approach is mentioned to sustainable development (Article 6(8)). However, these approaches are less prescribed and might be precisely defined in further negotiations.

Despite limitations in legal detail, lack of definition on carbon pricing, the Paris Agreement sets a clear target on stabilizing the climate change issues by mobilizing all Parties to UNFCCC, including developed and developing countries, and it gives a clear direction on how to enhance implementation to achieve the target. In this sense, the Paris Agreement provides positive roles in the following aspects:

- It is a first comprehensive climate deal on a global scope and provides a political momentum. Climate change is a consensus to all and needs to be addressed through the participation of all nations. Developed countries can continue taking the lead by undertaking economy-wide absolute emission reduction targets. While developing countries can enhance their efforts and move over time towards economy-wide emission reduction targets, under supports of developed countries.
- The Paris Agreement provides the mechanism for progressive preparation and technical implementation of NDCs. Although the current level of NDCs is not sufficient and needs to be improved in the future, a stocktaking mechanism ensures that this agreement could be ratified and enter

into force during a relative shorter period. And still the efforts on reduction targets could be made progressively.

- The Paris Agreement provides the guide line on how to address the global warming problems and its procedural approach requires further details to be confirmed. The forthcoming negotiations, including subsequent Conferences of Parties (COPs), have to determine the remaining technical details for the current provisions in the Paris Agreement. But it still provides the flexibility for each country to define and implement its own climate actions.

3

European Union Emission Trading Scheme

3.1 Introduction

To fight against the global warming problems and to reduce the GHG emissions, the European Union Emission Trading Scheme (EU ETS), also known as the European Union Emission Trading System, was launched Europe-wide in 2005. As of 2016, the system covers 31 European countries and more than 11,000 installations in the energy and industrial sectors. These sectors are responsible for around 50% of EU GHG emissions. The EU ETS was the first GHG emission trading system in the world and remains currently the world's largest.

3.1.1 Choosing the right mechanism

After the agreement of the Kyoto Protocol to the UNFCCC in 1997, the legally binding GHG reduction targets were set on an international level, first for the 37 industrialized nations. In order to meet the Kyoto commitments, the European countries needed to set a policy instrument to control the emissions in the European area. Therefore, the European Commission presented a green paper on Greenhouse gas emissions trading within the European Union in 2000 with its first ideas on the designs of the EU ETS. This led to the adoption of the EU ETS Directive (EU 03) in 2003 and the introduction of the EU ETS in 2005.

The European Emission Trading Scheme is designed as a cap-and-trade system. The cap means the EU sets a total volume of greenhouse gases that can be emitted by all participating installations. while trade means permits for emissions are then auctioned off or allocated for free, and can subsequently be traded within the system. Installations have to monitor and report their CO2 emissions, ensuring they have enough allowances to cover their emissions. If an installation has performed well in reducing its emissions and has leftover permits in its account, then it can sell them on the market. By contrast, if an installation's emissions exceed the level it is permitted by its allowances, it has to purchase more allowances from others, otherwise it will face a penalty. Such a system allows the participants to find the most cost-effective way for reducing emissions without significant government intervention.

The EU chose the cap-and-trade system as the best way to achieve the target of reducing the GHG emissions at least cost for all participants and the economy. Comparing with other policy instruments, the cap-and-trade structure has its own advantages. A command and control approach can regulate the installations directly and mandate a standard to all participants, but has little flexibility on controlling emission reduction for each company in a cost efficient way. Meanwhile, a tax or a subsidy approach provides more flexibility, but does not guarantee that the GHG emissions reduction target can be achieved, because companies can emit as much as they need. And it is difficult to determine the right level of the taxes and the subsidies of all sectors artificially. However, in a cap-and-trade system, trading allows market participants determine what the least-cost level is to meet the fixed cap. Therefore, the cap-and-trade system provides the flexibility on reducing the emission targets and guarantees that the targets will be achieved in a cost efficient way. According to EU (EC 15a), such a system provides the following key benefits:

1. **Certainty about quantity:** GHG emissions trading directly limits GHG emissions by setting a system cap that is designed to ensure compliance with the relevant commitment. There is certainty about the maximum quantity of GHG emissions for the period of time over which system caps are set. This is relevant for supporting the EU's international objectives and obligations and achieving environmental goals.

2. **Cost-effectiveness:** Trading reveals the carbon price to meet the desired target. The flexibility that trading brings means that all firms face the same carbon price and ensures that emissions are cut where it costs least to do so.

3. **Revenue:** If GHG emissions allowances are auctioned, this creates a source of revenue for governments, at least 50% of which should be used to fund measures to tackle climate change in the EU or other Member States.

4. **Minimizing risk to Member State budgets:** The EU ETS provides certainty to emissions reduction from installations responsible for around 50% of EU emissions. This reduces the risk that Member States will need to purchase additional international units to meet their international commitments under the Kyoto Protocol.

3.1.2 Compliance periods

The EU ETS is divided into several compliance phases:

- The first trading phase from 2005 to 2007;
- The second trading phase from 2008 to 2012;
- The third trading phase from 2013 to 2020;
- The post 2020 phase.

The first trading phase of EU ETS was seen as a trial phase, which helped to test the permit price formation of the European carbon market. It also helped to establish the infrastructure for the MRV process (monitoring, reporting and verification) of the EU ETS. The primary purpose of this phase was to ensure that the system would be functional ahead of 2008, so that the EU Member States would be able to meet their commitment targets under the Kyoto Protocol, which would be introduced in 2008. The EU ETS Directive (EU 03) also specified the provisions of use of international credits, which helped the businesses to use emission reduction units generated under the Kyoto Protocol to fulfill their compliance targets under the EU ETS. In this phase, companies were allowed to use emission reduction units from CDM for their compliance.

The second trading phase of EU ETS coincided with the first commitment period of the Kyoto Protocol ran from 2008 to 2012. The rules of trading of permits as well as the initial allocation of pollution permits have differed substantially between the first two phases. The total amount of permits allocated, was much lower in the second phase. The regulation of the transfer of pollution permits between phases changed as well. In this phase, besides international credits under CDM projects, businesses could also use emission reduction units generated under JI projects to meet their targets.

The third trading phase of EU ETS runs from 2012 to 2020, which coincides with the second commitment period of the Kyoto Protocol. Although the Doha Amendment has not been ratified by sufficient nations after its agreement in 2012 and therefore the second Kyoto commitment period is not yet legally binding, the EU as an independent jurisdiction has committed to a target and tracks its own climate policy. In the current phase, significant changes were made or are planned to improve the efficiency of the mechanism. For instance, less allowances are allocated for free to the industrial and power sectors, some short-term and long-term structural reforms are proposed to regulate the surplus of allowances and to rebalance the supply and demand of the carbon market.

The fourth trading phase is planned from 2021 to 2030, also known as the post-2020 phase. Based on the historical experience and the price behavior of the carbon permits, the European Commission presented in 2015 a legislative proposal to revise the EU ETS for the period after 2020. The EU set its 2030 climate and energy policy framework which included a binding target to cut emissions in EU territory by at least 40% below 1990 levels by 2030. This target was seen as part of the contribution of EU to the Paris Agreement, which was ratified by sufficient countries and came into force on 4th November 2016. To achieve the at least 40% EU target, all members of EU ETS have to reduce their emissions by 43% compared to 2005 level in the sectors covered by the ETS. For this target, the European Commission proposed a series of reforms within the system and the proposal was currently agreed informally by the European Parliament and the European council.

3.1.3 Objective of the system

To control the global warming problem and keep the climate change below 2°C, the EU planned to reduce the GHG emissions by 80%-95% by 2050 compared to 1990 levels in the context of similar reductions to be taken by developed countries as a group. To achieve this goal, the EU suggested a roadmap for its low carbon economy (EC 11). First, the roadmap suggested that, by 2050, the EU should cut its emissions to 80% below 1990 levels through domestic reductions alone, rather than relying on international credits. Other energy and climate targets were set to be achieved before 2050:

The EU's 2020 climate and energy package contains 3 key targets:

1. A reduction in EU GHG emissions of at least 20% below 1990 levels;
2. 20% of EU energy consumption to come from renewable resources;
3. A 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency.

These targets were set by EU leaders in 2007 and enacted in legislation in 2009 (EU 09a), (EU 09b), (EU 09c). The 20% emission reduction target by 2020 is an objective requiring efforts from all sectors across Europe. For the EU ETS, this target was transformed to a reduction of 21% emissions compared to 2005 levels by sectors covered by the EU ETS. Non-ETS sectors also required to reduce 10% of emissions compared to 2005. The target was set to be compared to the year 2005, because this was the starting year of the EU ETS. The Emission reduction targets as a part of the 2020 package for ETS and non-ETS sectors can be seen in Figure 3.1 below.

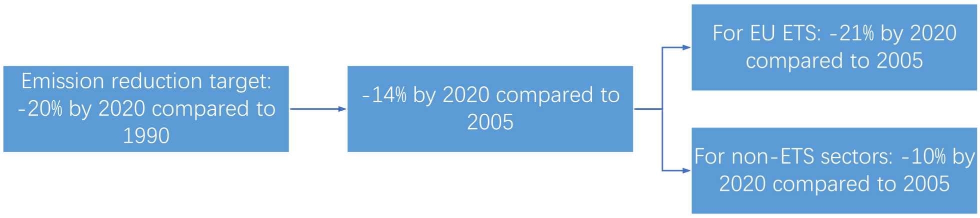
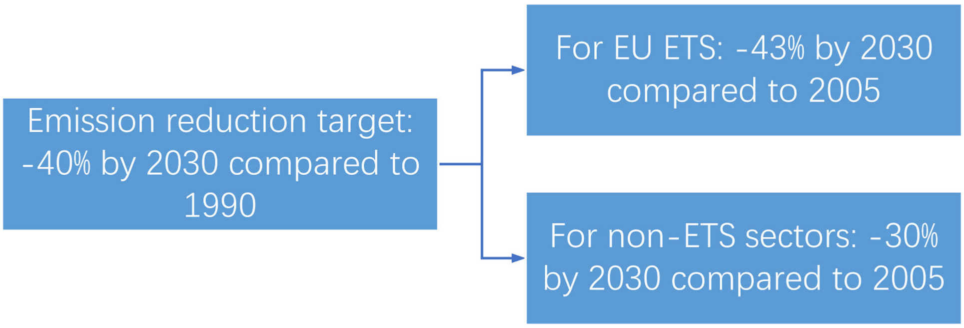


Figure 3.1: Emission reduction targets of EU's 2020 package for ETS and non-ETS sectors

The EU's 2030 climate and energy framework sets three key targets for the year 2030:

1. A reduction of GHG emissions by at least 40% below the 1990 level by 2030 to be achieved domestically;
2. An increase of the EU-wide renewable energy share to at least 27%; and
3. Improving energy efficiency by at least 27% by 2030, with 30% by 2030 in mind.

This framework was proposed on January 2014 and was adopted by EU leaders in October 2014 (EC 13), (EC 14a). To achieve the at least 40% emission reduction target, sectors covered by the EU ETS would have to cut their total emissions by 43% compared to the 2005 levels. Meanwhile, non-ETS sectors would have to cut emissions by 30% compared to 2005 and this target needs to be translated into individual binding targets for all Member States of the EU ETS. Figure 3.2 shows the emission reduction targets of the 2030 framework for ETS and non-ETS sectors.



Emission reduction target: -40% by 2030 compared to 1990

For EU ETS: -43% by 2030 compared to 2005

For non-ETS sectors: -30% by 2030 compared to 2005

Figure 3.2: Emission reduction targets of EU's 2030 framework for ETS and non-ETS sectors

3.1.4 Other main features

The scope of the EU ETS extended since the beginning of the first trading phase in 2005. It covered not only the Member States of the European Union, but also most nations in the European Free Trade Association (EFTA). With the start of the first trading phase of EU ETS in 2005, all 25 EU Member

States were within the system. This number then increased to 27 when Romania and Bulgaria joined the EU in 2007. From the second trading phase in 2008, Norway, Iceland and Liechtenstein, known as the EFTA countries (except for Switzerland) joined the EU ETS. These countries together with the members of EU were known as the Member States of the European Economic Area (EEA). In phase 3, Croatia became a Member State of EU and therefore joined the EU ETS automatically in January 2013. Currently, there are 31 states in the EU ETS totally.

The UNFCCC and the Kyoto Protocol defined six main GHG emissions. However, these greenhouse gases are not all covered by the EU ETS. The first trading phase only covered the Carbon dioxide (CO2). In the phase 2, the Nitrous oxide (N2O) was also covered by the ETS, but was only included voluntarily at the discretion of EU members. In phase 3, Nitrous oxide (N2O) and certain Perfluorocarbon (PFC) emissions were included as well from aluminum production.

The EU ETS covered GHG emissions from mainly two carbon intensive sectors, the power and the manufacturing industry. Since the first trading phase, power stations and other combustion plants with more than 20 MW thermal rated input, oil refineries, coke ovens, iron and steel, cement clinker, glass and ceramics, lime, bricks, paper and board were covered in the system. In 2012, emissions from aviation sector was also included in phase 2. From phase 3, the sectoral scope was expanded to aluminum sectors, carbon capture and storage, petrochemicals and other chemicals. The aviation sector was also included in the EU ETS within the third trading phase, but only emissions from flights within the EEA were limited in the period 2013 to 2016.

Table 3.1 summaries the main features of the EU ETS mentioned above for its different trading phases.

3.1.5 Registry, MRV and compliance

Registry and monitoring, reporting and verification (MRV) are important systems to guarantee the EU ETS to be operated effectively. The registry keeps track of the ownership of allowances within the EU ETS, while the MRV ensures

Features	**Phase 1: 2005-2007**	**Phase 2: 2008-2012**	**Phase 3: 2013-2020**
Member States	25 EU Member States, extended to Romania and Bulgaria in 2007	27 EU Member States with Norway, Iceland and Lichtenstein	30 EEA Member States with Croatia in 2013
GHG emissions	CO2	CO2, N2O (voluntary)	CO2, N2O, certain PFC from aluminum production
Sectors	Power stations and other combustion plants $>$ 20 MW, Oil refineries, Coke ovens, Iron and steel, Cement clinker, Glass and ceramics, Lime, Bricks, Paper and board	Same as phase 1 and Aviation	Same as phase 1 and Aviation from 2013-2016, Aluminum, Petrochemicals, Ammonia, Nitric, adipic and glyoxylic acid production, CO2 capture and transport in pipelines and geological storage

Table 3.1: Main features of EU ETS in different trading phases

that the compliance process of the EU ETS to be functional and transparent.

The Union registry is an electronic accounting system that accounts the allowances issued under the EU ETS and international credits for its all stationary installations. It covers all 31 participants of the system. The Union registry records the following data:

- The list of all installations covered by the ETS Directive and the allowances assigned for free to each installation of the Member States as well as the free allocation to aircraft operators.
- The accounts of the Member States, companies and individuals holding allowances and eligible international credits, such as CERs and ERUs.
- All the transactions of allowances and international credits performed by the account holders.
- The annual verified emissions of these installations and aircraft operators.
- The annual reconciliation of allowances, i.e. the number of allowances that must be surrendered by the companies to cover their annual verified emissions.

Since the beginning of the EU ETS, these data were recorded by the national EU ETS registries that were formerly hosted by each country of the Member States. The single Union registry was operated by the European Commission on a Europe-wide level and replaced all these national registries. In order to be able to participate in the EU ETS and perform transactions, a company or an individual must hold an account in the Union registry.

The transaction data are recorded and authorized by the European Union Transaction Log (EUTL). It checks the data and ensures that all transactions of carbon permits between different accounts is consistent with EU ETS rules. Before the activation of the Union registry, the Community Independent Transaction Log (CITL) was used and provided similar function to record the transaction data. The CITL was then replaced by the EUTL after the operation of the Union registry in 2012.

It is worth to mention that the Union registry is a single European registry that records the flow of allowances and international credits of Kyoto Protocol between different Member States within the EU ETS and from outside. Meanwhile, the International Transaction Log (ITL), administrated by the UNFCCC under the Kyoto Protocol, accounts the transfer information of all international credits to the countries under the EU ETS and other non-ETS countries. Therefore, the Kyoto credits used in the EU ETS are subject to a check by both the EUTL and the ITL.

The monitoring, reporting and verification process is also a key factor to guarantee the EU ETS to be operated functionally. Every year, each installation or aircraft operator is required to prepare a monitoring plan and submit it to the Competent Authority under the EU ETS. The monitoring plan must contain information and activities of the corresponding operators to be monitored and their chosen monitoring methodology, measurement systems, data management and control procedures. Moreover, operators need to report their annual emissions through an emission report, which contains all the data of direct GHG emissions of the installation or the aircraft in the given year. The report must be verified by an independent accredited verifier before it is submitted. The annual procedure of monitoring, reporting and verification (MRV) is known as the EU ETS compliance cycle.

In the history of the EU ETS, the regulation for monitoring and reporting were improved to make sure the system to be operated more effectively. The current rules related to the compliance cycle are set out in two regulations: The Monitoring and Reporting Regulation (MRR) - Commission Regulation (EU) No 601/2012 (EU 12a) and the Accreditation and Verification Regulation (AVR) - Commission Regulation (EU) No 600/2012 (EU 12b). Since the beginning of the third trading phase, the MRV process has to be in line with these two regulations.

The EU ETS compliance cycle contains the following steps:

- Operators of an installation or aircraft must prepare and submit a monitoring plan to their corresponding Competent Authority and their GHG permit applications at the beginning of the year.

- The monitoring plans needed to be approved by the Competent Authority.
- Operators implement their monitoring during the year and update the plan and submit it to the Competent Authority for approval, in case the monitoring methodology needs to be changed.
- Operators have to submit an annual GHG emissions report to the Authority before it was verified by an independent verifier.
- Once the report is submitted, operators must surrender allowances before the deadline on 30 April.
- If necessary, operators need to submit a report on improvements of the monitoring methodology.
- Verifiers start the verification process usually in the third quarter of the current year.

The total MRV process covers the whole calendar year. However, some procedures such as submitting the verified emissions report and surrendering allowances can only take place in the subsequent year. The following Figure 3.3 demonstrates the EU ETS compliance cycle according to its chronological order.

Figure 3.3: The chronological EU ETS compliance cycle

Borrowing, banking and withdrawal

The design of compliance cycle makes it possible for companies to borrow allowances from a future allocation for one year. Operators receive their free allowances in February each year to meet their compliance of the current year, but they have to surrender the corresponding volume of allowances at the end of April for the previous year. Therefore, operators are allowed to use some of their new allocated allowances, assigned by February, to cover their emissions in the previous year at the compliance deadline by April. This operation is technically possible and is called borrowing. Borrowing is only allowed within a trading phase, borrowing allowances form the first year of a new trading phase for the use of the last year of a previous trading phase is not permitted, e.g. borrowing cannot occur between 2012 and 2013.

Conversely, operators may also have surplus of allowances at the end of a trading year. Since the trading phase 2, operators are allowed to transfer their unused allowances of the trading year to the subsequent trading year. This operation is called banking. Not like borrowing, banking is permitted not only between different trading years, but also between different trading phases since 2008. Between the second and the third phases, unlimited allowances were allowed to be banked, meaning all used allowances before 2012 can be used in phase 3. This volume was transferred to accounts of operators automatically at no cost to them. Therefore, the volume of allowances issued in phase 3 under the cap was added to the banked volume.

Additionally, in each trading phase, if a participant of EU ETS does not have sufficient allowances for its annual compliance, it must be fined. This could occur when if an operator does not have sufficient allowances and refuses to or cannot borrow them from the subsequent year and also does not purchase the shortfall volume from the market. The penalty is 40 for each tCO2 during phase 1 and 100 since phase 2, adjusted with the EU inflation rate. The penalty is imposed by the relevant authority of each member state. Furthermore, the shortfall volume of allowances must be added to the compliance target for the next year, or say, the shortfall volume must be withdrew from the next year's volume.

3.2 Allocation of Allowances

As a cap-and-trade system, the total volume of annual greenhouse gases emitted by the installations of power plants and factories and aircraft operators covered by the EU ETS are set not to exceed a maximum limit. Such a limit is called the cap. Once the cap is determined, companies will receive the corresponding volume of carbon permits, or say allowances, for their compliance. The allowances are the rights for companies to emit the same tonnes of carbon dioxide or other equivalent amount of greenhouse gases. The allowances are allocated for free or auctioned to operators, so that companies are able to trade them in the secondary market.

3.2.1 Emissions cap

Before each trading phase of EU ETS, a central cap at the EU level must be determined by the European Commission based on the provisions of the ETS directive (EU 03), which is the main legislation of the EU ETS. Since the EU ETS has special rules for the aircraft operators, i.e. aviation sector can use any kinds of allowances for compliance purposes, but stationary installations cannot use aviation allowances. The cap in the EU ETS is usually separated into two ways: a cap for all stationary installations and a cap for the aviation.

In phase 1 (2005-2007) and phase 2 (2008-2012), the cap was set via the National Allocation Plans (NAPs). In these two phases, most of allowances were allocated for free, the proportion of free allocation all installations received was around 95% in phase 1 and then fell slightly to around 90% in phase 2. Each Member State of EU ETS needed to prepare a document specifying the number of allowances to be allocated to its installations during the coming trading period. The Commission assessed the documents of NAPs and approved the number to be allocated, or amended it if necessary. The total cap was then determined by the collection of all NAPs.

In the trading phase 3 (2013-2020), the way of determination of the cap was changed. Around 50% of allowances in the EU ETS were planned to be auctioned and therefore would not be allocated for free. A National Implementation Measure (NIM) was used by each Member State to replace the NAP.

Member States were still required to submit their plans including detailed information on allocating free allowances for their domestic installations. However, the total cap set for phase 3 was no more fixed and would decrease each year by applying a linear reduction factor (LRF).

The linear reduction factor was introduced to ensure the overall 20% reduction target and would result in a 21% reduction emissions within the EU ETS by 2020 compared to 2005. Since 2013, the annual cap would decrease each year by a linear factor of 1.74% compared to 2010. The number of total allowances to be assigned from 2013 was determined by the following elements:

1. The number of allowances which were issued by Member States under EU ETS in accordance with the Commission Decisions on the National Allocation Plans of Member States for the period from 2008 to 2012. (The decisions for each Member State can be found here `https://ec.europa.eu/clima/policies/ets/pre2013/nap_en#tab-0-1`);
2. The average number of allowances which were issued each year of the period by Member States to new installations that entered the EU ETS; And
3. The number of allowances that takes into account the effect of the extended scope of the EU ETS, i.e. installations which were included as from the beginning of the third trading phase in 2013.

By taking into account these factors, the quantity of cap for 2013 was calculated at 2,084,301,856 allowances. Meanwhile, the linear reduction factor implied that the amounts of the reduction was 38,264,246 each year from 2013 to 2020. This quantity of annual reduction is consistent with the 21% of emissions reduction target of EU ETS by 2020. Table 3.2 shows the total annual cap of EU ETS throughout the trading phase 3.

Unlike stationary installations, aviation sector within the EU ETS will continue to receive free emission allowances throughout the trading phase 3. The cap on total aviation allowances for phase 3 was set at 210,349,264 originally and would increase by 116,524 allowances per year from 2014 onwards. 82% of this amount would be allocated to the aircraft operators for free. 15% would

Year	Annual cap	Reduction volume
2013	2,084,301,856	38,264,246
2014	2,046,037,610	38,264,246
2015	2,007,773,364	38,264,246
2016	1,969,509,118	38,264,246
2017	1,931,244,872	38,264,246
2018	1,892,980,626	38,264,246
2019	1,854,716,380	38,264,246
2020	1,816,452,134	38,264,246

Table 3.2: Cap of EU ETS for trading phase 3 excluding aviation

be auctioned and the left 3% would be taken into a reserve for new entrants or fast-growing operators. Figure 3.4 illustrates the cap in the EU ETS separated into the stationary installations and the aviation sector.

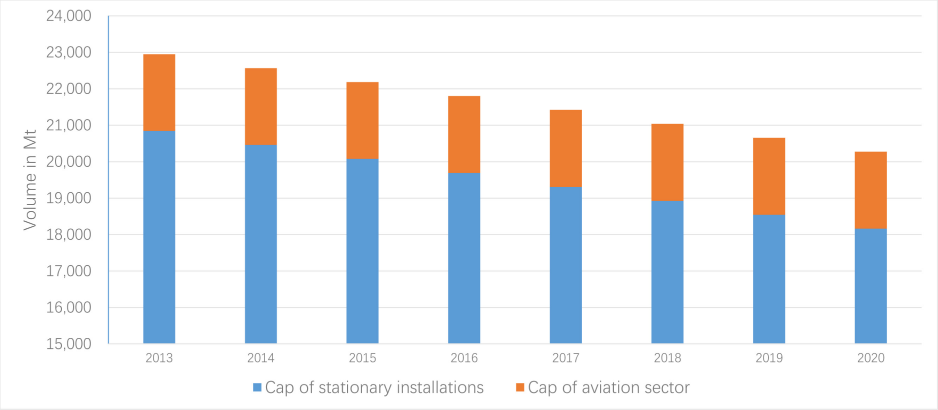


Figure 3.4: Cap of phase 3 in stationary installations and the aviation sector

3.2.2 Free allocation of allowances

Free allocation and auction of allowances are two main methods to assign the carbon permits to their users in the EU ETS. Rules of free allocation were changed in different trading phases based on different function and objective to be achieved in each phase.

The first trading phase was considered as a learning by doing period as the EU ETS was first established and would be tested to be functional. As a preparation for phase 2, the phase 1 did not set any strict emissions reduction target. Almost all allowances were allocated to the power plants and energy intensive industries for free through grandfathering. Grandfathering means companies receive their free allowances based on their historical GHG emissions. This method was then criticized as it provided emitters large windfall profits and less incentive to reduce their emissions. Then in the second trading phase, the EU ETS needed to function effectively so that the EU was able to meet its Kyoto commitment targets - together with other emission reductions and climate actions outside the EU ETS. The proportion of free allocation under EU ETS fell to around 90% in this phase, most of them were allocated still through grandfathering, but some Member States began to set their free allocations through benchmarking. In the trading phase 3, in order to achieve the 21% emission reduction target under EU ETS, significant changes were made by EU on free allocation rules. These rule can be specified from the following 3 aspects.

Free allocation to industries

Industrial sectors did not receive most of their allowances for free in this phase. In principle, free allocations decrease each year throughout the trading phase 3. How many allowances an industrial company or a sector can receive was classified in two different ways.

First, if a sector is deemed to face a significant risk of carbon leakage from exposure to non-Europe competition due to the carbon prices of the EU ETS, this sector will receive 100% of its emission allowances for free throughout the phase 3. Carbon leakage is the risk that companies will face increased costs due to the local climate policies and therefore prefer to transfer their production to other countries that have lower standards or cheaper measures to cut GHG emissions. The result is that transfer of production would not help to abatement and lead to an increase of global GHG emissions. According to the ETS Directive (EU 03) (Article 10a), a sector or a sub-sector is defined to be exposed to a significant risk of carbon leakage if the following criteria are fulfilled:

- Its direct and indirect costs induced by the implementation of the directive would increase production cost, calculated as a proportion of the gross value added, by at least 5%; and

- The sector's trade intensity with non-EU countries (imports and exports) is above 10%.

A sector or sub-sector is also deemed to be exposed if:

- The sum of direct and indirect additional costs is at least 30%; or
- The non-EU trade intensity is above 30%.

To avoid the carbon leakage problem, a carbon leakage list of sectors and subsectors was drawn up by the European Commission. The first list (EU 10a) was applied for the first 2 trading years of phase 3 (2013-2014). The second list (EU 14a) will be applied from 2015 to 2019 and the subsequent lists will be functional for each 5 years after 2019.

Second, if a sector is not on the carbon leakage list, it will receive 80% of its allowances for free in 2013 and the proportion will decrease gradually year-on-year to 30% by 2020. Table 3.3 shows the share of free allocation that industry sectors can receive in the third phase of EU ETS. Industry sectors are divided into two categories, one includes sectors exposed to carbon leakage (C.L.) risk, the other one not.

Year	Sectors not on C.L. list	Sectors exposed to C.L.
2013	80%	100%
2014	72.86%	100%
2015	65.71%	100%
2016	58.57%	100%
2017	51.43%	100%
2018	44.29%	100%
2019	37.14%	100%
2020	30%	100%

Table 3.3: Share of allocations for industries in trading phase 3 - Data source: European Commission

Another significant change of allocation rules is that all sectors receive their free allocations based on benchmarks, no more on grandfathering. The benchmark is developed for each product produced by the industrial installations.

Generally speaking, a benchmark of a product is determined by the average greenhouse gas emissions that the best performing 10% of the installations produce this product in the EU. Installations receive their free allocations based on the benchmark of a product, produced by these installations. If they meet their benchmarks, these installations will have sufficient allowances to cover their emissions. Otherwise, they can either reduce their emissions by improving their producing technologies or purchasing additional allowances or international credits from the market.

As described in the previous subsection, Member States have to submit their National Implementation Measures (NIMs) to the Commission, including the numbers of free allowances their domestic installations need each year throughout the third trading phase. The commission have to check the NIMs and approve them or amend them if necessary. Countries receive their allocations and issue the allowances to its companies annually. To make sure that the total required free allowances and other assigned carbon permits do not exceed the annual cap under the entire EU ETS, a cross-sectoral correction factor (CSCF) is applied to adjust the number of free allowances for the installations. This factor reduced the free allocations by around 5.73% in 2013 and increases progressively each year to around 17.56% in 2020, as the cap decreases annually during this period. Table 3.4 shows these factors throughout the phase 3, which was determined by the European Commission in (EU 13).

Year	CSCF
2013	94.272151%
2014	92.634731%
2015	90.978052%
2016	89.304105%
2017	87.612124%
2018	85.903685%
2019	84.173950%
2020	82.438204%

Table 3.4: The cross-sectoral correction factor (CSCF) from 2013 to 2020 - Source: European Commission

The number of free allocation for each year can be calculated by using the following formula:

$$\text{Number of allocation} = \text{Benchmark} \times \text{Historical activity level} \times \text{Carbon leakage exposure factor} \times \text{Cross-sectoral correction factor/Linear reduction factor},$$

where the benchmarks are calculated by the EC given in (EU 11), the historical activity level (HAL) indicates the historical production corresponding to the applicable benchmark, the Carbon leakage exposure factor (CLEF) is given by Table 3.3, the Cross-sectoral correction factor (CSCF) is given by Table 3.4, and the Linear reduction factor (LRF) is in line with the factor of 1.74% specified in the previous subsection, decreasing each year from 2013 to 2020, to electricity generators for their heat production. Detailized explanation on calculation methodology to determine free allocation can be found in (EC 12).

Free allocation to electricity generators

Generally, power generations do not receive any allowances for free since the beginning of the third trading phase. However, there are some exceptions for some Member States.

In 2004, 10 countries became new Member States under EU and joined the EU ETS automatically. They are Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Lithuania, Poland, Romania, Latvia and Malta. These countries are allowed to receive free allowances to compliance for their power plants, so that they are able to prevent too sharp increases in electricity prices for domestic customers and will have sufficient time for making the transition to less carbon-intensive electricity generations. Under the ETS Directive, the level of free allocation in 2013 must not exceed 70% of the allowances needed to cover emissions from the power sector of these countries. This level will decrease yearly and will reach 0% by 2020. All of these countries are eligible to receive free derogation volume, but Latvia and Malta chose not to it. The other 8 courtiers drawn up plans setting out investments to be financed through the free allocation with aim to modernizing their electricity sectors.

Free allocation to aviation sector

Aviation sector joined the EU ETS since 1 January 2012. In the same year, 85% of allowances were allocated for free based on its benchmarks. For the phase 3 from 2013 to 2020, 82% of all allowances are to be allocated for free based on benchmarks and 15% are to be auctioned. The remaining 3% constitutes a special reserve for new entrants and fast growing airlines.

3.2.3 Auction

Almost all allowances allocated in the first and second trading phases of EU ETS were free of charge, only a small portion was assigned through auctioning. However, auction design and organization in these two phases was not determined centrally by the European Commission, but individually by a few Member States of EU. In phase 1, Member States were allowed to auction up to 5% of the emission allowances, but only four countries chose to use auction among all 27 countries of EU ETS. Three of them, Hungary, Ireland and Lithuania used single-round, sealed-bid, uniform-price auctions, while Denmark originally planned to auction 5% of its allocation, but then decided to sell the allowances through the brokered market instead of auctioning after its assessment. The explanation for this decision was that a professional broker would have the ability to sell the bulk of the allowances in high-price periods, which was deemed better than if unprofessional government officials decided when to sell (Faze 08). Table 3.5 indicates the quantity of allowances set aside for auctioning by these countries in the first trading phase. In total, the amount of allowances auctioned by Hungary, Ireland and Lithuania only took around 0.2% of all allowances allocated for free.

Country	**Allowances**	**Percentage**
Hungary	1420000	2.5%
Ireland	502201	0.75%
Lithuania	552000	1.5%
Denmark	5025000	5%
EU ETS	7499201	0.2%

Table 3.5: Quantity of allowances set aside for auctioning of EU ETS in phase 1 - Data source: European Commission

Then in the second trading phase, the proportion of auction allowed was up to 10%. Four countries, Austria, Germany, Netherland and UK used auction partially instead of free allocation. Their auctions were also designed in favor of a single-round, sealed-bid, uniform-price mechanism. Their annual quantity for auctioning can be seen in Table 3.6 below. In total, the quantity of allowances auctioned amounts to around 4% of all allocation during this period (BCKS 10).

Country	**Allowances**	**Percentage**
Austria	400000	1.3%
Germany	40000000	9%
Netherland	3200000	3.7%
UK	17000000	7%
EU ETS	89400000	4%

Table 3.6: Annual quantity of allowances to be auctioned in phase 2 - Data source: European Commission

Since 2013 of phase 3, auctioning is considered to be the default method of allocation within the EU ETS. The Commission increased the proportion of auction sharply in this period, especially to the power sector. For power plants, all allowances are to be auctioned, only eight Member States can receive free allocations partially under certain rules described in the previous subsection. However, the proportion of free allocation for these eight countries decreases each year and will be 0% by 2020. In industry sector, a transition to auctioning takes place progressively. Sectors deemed to be exposed to carbon leakage risk still receive 100% of allowances for free. Other industry sectors receive 80% of free allowances in 2013, and this percentage decreases to 30% in 2020 progressively. Allowances not allocated for free are to be auctioned for them. In the aviation sector, 15% of allowances in circulation will be auctioned throughout the period. In total, over 40% of allowances were through auctioning in 2013 and this proportion is to be increased over the period. During the third trading phase from 2013 to 2020, about 57% of total amount of allowances are to be auctioned. This proportion is estimated by the European Commission and it implies an amount of 8,176,193,157 of allowances.

The establishment of an auction mechanism was stated in the revised EU ETS Directive (EU 09c) in 2009. Detailed rules of auctioning of allowances is governed by the EU ETS Auctioning Regulation (EU 10b). According to Article 10(1) of the Directive, the allowances to be auctioned have to be distributed in three different ways:

- 88% of the allowances are to be auctioned in 2013 to 2020 are distributed to the EU Member States on the basis of their share of verified emissions from EU ETS installations in 2005 or the average of the 2005-2007 period, whichever one is the highest;
- 10% are allocated to the least wealthy EU Member States as an additional source of revenue to help them invest in reducing the carbon intensity of their economies and adapting to climate change;
- The remaining 2% is given as a 'Kyoto bonus' to nine EU Member States which by 2005 have reduced their greenhouse gas emissions by at least 20% of levels in their base year or period. These are Bulgaria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania and Slovakia.

In this phase, countries under the EU ETS have the flexibility to choose to perform auction on an opt-out platform, or on a common auction platform. Currently, Germany, Poland and UK chose to use their own auction platforms and other Member States are using the common platform. Germany appointed European Energy Exchange (EEX) in Leipzig as its auction platform. The UK appointed Intercontinental Exchange (ICE) in London as its auction platform. Poland did not have its own platform and therefore chose to contract EEX to auction on its behalf. The EEX was also appointed as the common auction platform for the other countries under EU ETS since beginning of 2013. On 13 July 2016, the EEX was reappointed by the Commission to auction general and aviation allowances as the common platform on behalf of 25 Member States for another period of up to five years. Each year, ICE and EEX have to publish an auction calendar with exact dates and volumes of general allowances and aviation allowances to be auctioned per Member State. And they also have to publish information on the auction results after each auction was performed. Table 3.7 specifies where, when and how often the auctions are taking place.

Participants	**Platform**	**Auction time**
25 Member States/ EEA EFTA states	EEX	Weekly on Mondays, Tuesdays and Thursdays
Germany	EEX	Weekly on Fridays
Poland	EEX	Monthly on Wednesdays
UK	ICE	Fortnightly on Wednesdays

Table 3.7: Timing, place and frequency of EU ETS auctions

Based on the auction regulation and information described above, the amount of general allowances to be auctioned in the period from 2013 to 2020 can be calculated approximately and therefore can be used by the Commission on determining the annual auction calendar. This amount can be seen in Figure 3.5 below. The auction volume is calculated under the consideration of back-loading mechanism of EU ETS. The back-loading mechanism is a structural reform measure of EU ETS and it means to freeze the auctioning of some CO2 allowances, so as to raise the carbon price and thus encourage companies under EU ETS to invest in low-carbon innovation. This will be specified in subsection 3.4.1 of this chapter.

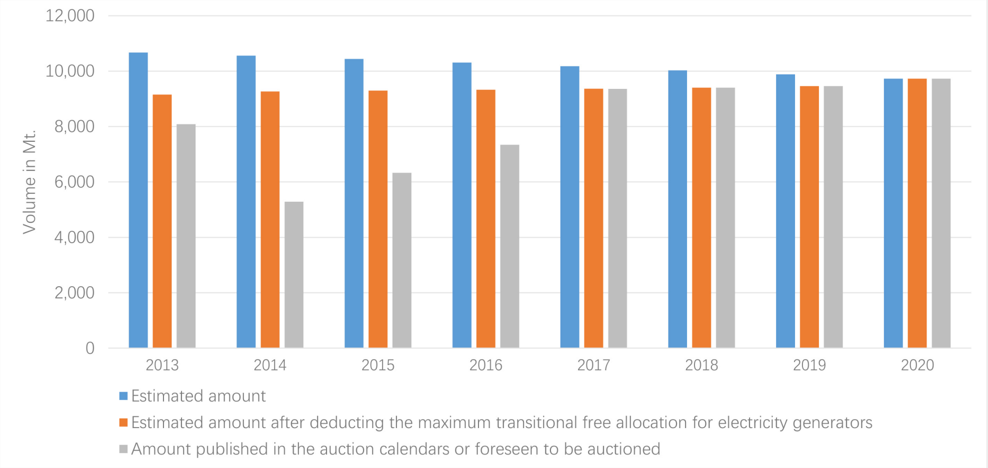


Figure 3.5: Estimated amount of allowances to be auctioned in phase 3
Data source: European Commission

3.3 Trading Permits and Price Behavior

3.3.1 European Union Allowances

The Commission as the central authority allocates carbon permits free of charge or sells them via auction to operators. Operators are required to hold permits in amount equal to their emissions for compliance. In case of lack of permits, operators have to buy additional permits from the market. Or operators with surplus of permits can choose to sell them in the market to increase their profits. The European Union Allowance (EUA) is officially the carbon permits used within the EU ETS and represents a permit to emit one tCO2. For the aviation sector, the European Union Aviation Allowance (EUAA) is an emission right that used to cover emissions by allowed airlines. Following types of EUA products can be traded in the market:

EUA spots: the spot trade means the purchase or sale of EUA for immediate delivery. Under the EU ETS, the spot date should take place within two business days after the trade is agreed. A spot contract is in contrast with a contract of financial derivatives, which usually has its delivery and payment at a future time. This means that spot trading is currently not regulated as financial instruments at the EU level by the Markets in Financial Instruments Directive (MiFID). Therefore, exchanges packaged emission allowances spot trading as financial instruments, called daily futures, so that spot trading is also able to be supervised under MiFID. Both ICE and EEX offer EUA spot daily futures for market participants.

EUA forwards: this is a contract made by two parties to buy or sell an amount of EUAs on a future date. A forward contract can be understood as an unstandardized futures contract which takes place over-the-counter (OTC) instead of via an exchange.

EUA futures: this is a standardized contract between two parties to buy or sell an amount of EUAs with delivery and payment on a future date. The contract is negotiated at a futures exchange, with acts as an intermediary between the two parties.

EUA options: this gives the buyers of the option the right, but not the obligation to trade an amount of EUAs at a fixed price on a future date. Call and put options are both offered by the ICE and EEX to participants for hedging their risks and managing their carbon permit portfolios.

EUA swaps: an EUA swap does not have the same meaning with a normal swap in a financial market, which allows a party to change its exposure or risk from floating prices to fixed prices. This is a derivative contract allows a party to change an amount of EUAs for the same quantity of international credits. Both EUAs and international credits are eligible for compliance, but international credits have usually lower prices compared to EUAs and therefore have to be discounted by trading. This means sellers of EUAs can receive credits as well as price differential between the two units. Another form of swap contract used in the EU ETS is the so-called maturity swap. Maturity swaps describe swaps between allowances or credits of the same type with different delivery dates. For example, a company can sell spot allowances and buy forward allowances at the same time to avoid price risks.

For the aviation sector, ICE and EEX also offer the EUAA futures. Additionally, EEX provides EUAA OTC trade registration. However, no options are provided by both of the exchanges.

Trading EUAs can be engaged directly between two parties referred to as over-the-counter (OTC) or through exchanges. Operators are also able to auction EUAs via ICE or EEX. The most participants are operators from energy or industry companies with compliance purpose as well as financial intermediaries. In principal, any participant with an account in the EU registry can engage the trading. The changes in holding of their emission allowances are recorded in the registry by the European Union Transaction Log (EUTL). The trading volume of EUAs increased sharply each year in the first and second trading phases, but decreased since the third phase as shown in Figure 3.6.

3.3.2 International credits

Beside EUAs, international credits created by the Kyoto Protocol can be also used for compliance in the EU ETS. The credits are from two Kyoto projects:

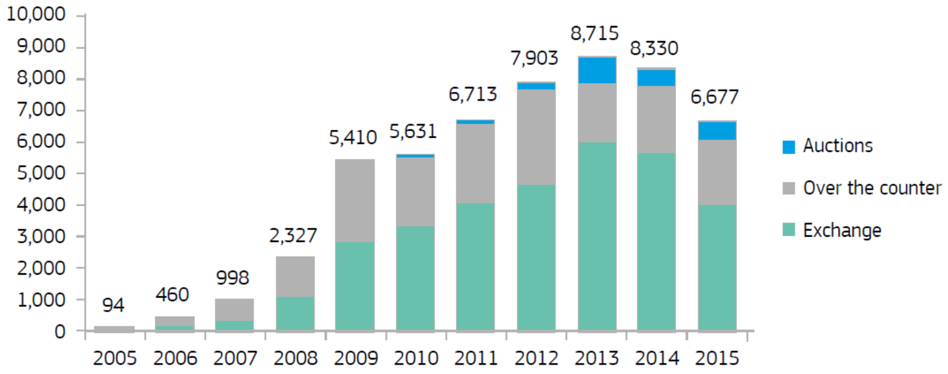


Figure 3.6: Trading volume of EUAs from 2005 to 2015 Source: European Commission EU ETS factsheet, Sep. 2016. Originally data from Bloomberg LP, ICE, EEX, NYMEX, Bluenext, CCX, Greenmarket, Nordpool, and UNFCCC.

- The Clean Development Mechanism (CDM) allows industrialized countries, defied as Annex I countries of the Kyoto Protocol, to invest in projects in developing countries and help them to reduce their domestic emissions. The industrialized countries receive then a certain number of saleable Certified Emission Reduction (CER) credits, generated by the project and use them for their own compliance.

- The Joint Implementation (JI) allows Annex I countries of the Kyoto Protocol to meet part of their required emission reduction targets by paying for projects in other Annex I countries. The JI projects provide for the creation of emission reduction units (ERUs).

Each unit of CERs and ERUs are equivalent to one tonne of CO2e, and both can be used to fulfill part of reduction targets under the EU ETS until the end of phase 3. However, the usage of the credits is under certain qualitative and quantitative restrictions.

Under the qualitative restrictions, the EU legislation specifies that both credits can be used from all types of projects with the following exceptions:

- Land-use, land-use change and forestry (LULUCF) projects;
- Nuclear projects;
- Large hydropower projects with more than 20MW of installed capacity subject to certain conditions;

- HFC-23 destruction projects (as of 1 May 2013); and
- N2O destruction projects from adipic acid production (as of 1 May 2013).

Additionally, CERs and ERUs representing emissions reductions achieved after 31 December 2012 are prohibited. CERs generated from CDM projects registered after that date are only eligible in the EU ETS if the projects are hosted in least-developing countries as defined by UN. ERUs from JI projects after that date cannot be used for compliance in countries that have not ratified the second Kyoto commitment period.

Under the quantitative restrictions, the usage of international credits is regulated by the EU legislation for different trading periods and sectors.

In phase 2, credits were permitted up to a percentage determined by the National Allocation Plans (NAPs) for different installations. Aviation operators have a limit up to 15% of their surrender obligation. All unused credits were transferred directly into phase 3. In total, around 1.06 billion international credits were used in phase 2.

For phase 3, the maximum quantity of eligible international credits each installation can use must fulfill the following conditions:

- Installations which already fell into the scope of the EU ETS in the period 2008 to 2012 may use credits in the period 2008 to 2020 up to a limit of 11% of their allocation for 2008 to 2012;

- New entrants in the period starting in 2013 and installations which did not fall under the EU ETS in the period until 2012, and thus did not receive any allocation, may use credits up to a limit of 4.5% of their verified emissions in the period 2013 to 2020; and

- Aviation operators may use project credits up to a limit of 1.5% of their verified emissions in the period 2013 to 2020.

Furthermore, the total use of credits from 2008 to 2020 is not allowed to exceed 50% of the total overall reductions below 2005 levels made by the sectors under the EU ETS. In phase 3, both credits are no longer compliance units within the EU ETS and therefore must be exchanged for EU allowances.

3.3.3 Price behavior

Trading carbon permits is active in both primary and secondary market. The primary market is defined as the market, which brings new carbon permits into itself, either through free allocation and auction in case of EUAs, or through the CDM and the JI projects in case of CERs and ERUs. The secondary market means that the market trades already issued allowances and credits. In practice, the trading volume in the secondary market is more than in the primary market.

Both EUAs and CERs can be traded in the spot and futures markets, but the trading volume of EUAs in the futures market is far greater than in the spot market. Currently, carbon products are mainly tradable on the following four exchanges:

- The Intercontinental Exchange (ICE) in London,
- The European Energy Exchange (EEX) in Leipzig,
- The NASDAQ OMX Commodities Europe (NOMX) in Oslo, and
- The New York Mercantile Exchange (NYMEX) in New York.

The ICE has by far the most market share of traded EUAs. Previous exchanges such as the Bluenext, the Energy Exchange Austria (EXAA), the Climex and the Greenmarket-Exchange have suspended the emission trading business. Table 3.8 specifies the carbon products in these exchanges in the primary and the secondary market.

On the secondary market by 2013, ICE took a share of 93.31% of overall EUA traded volume and is clearly the biggest player in the market. The other 3 market players only had a market share of 6.69%. Figure 3.7 shows the share of traded volume of each exchange.

Comparing traded volume on different types of contracts, it can be concluded that the futures are by far the most traded contracts in the EU ETS. The traded volume of spot, futures and options on EUA, CER and ERU in

Exchanges	**EUA**	**EUAA**	**CER**	**ERU**
ICE	Auctions (UK), Spot, Futures, Options	Auctions (UK), Futures	Spot, Futures, Options	Futures, Options
EEX	Auctions (Germany, Poland, EU), Spot, Futures	Auctions (Germany, Poland, EU), Spot, Futures	Spot, Futures	Futures
NOMX	Spot, Futures, Options	-	Spot, Futures, Options	-
NYMEX	Spot, Futures, Options	Futures	Futures, Options	Futures, Options

Table 3.8: Emission products in exchanges

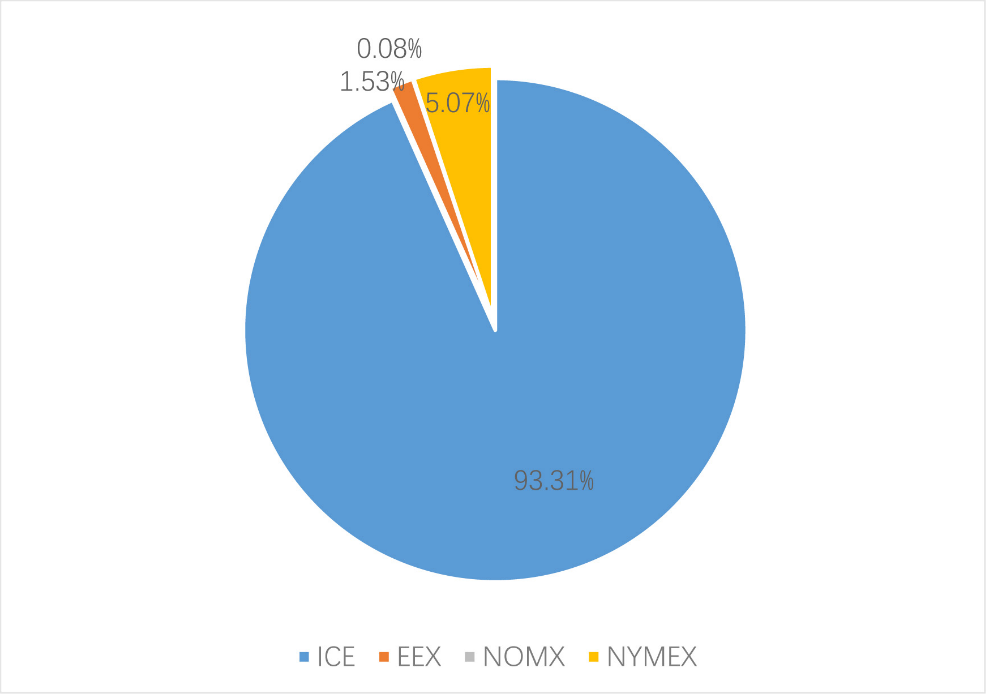


Figure 3.7: Share of traded volume of exchanges in 2013 Data source: DEHSt, originally from Point Carbon.

2012 and 2013 can be seen in Table 3.9 below.

Product/Year	2012	2013
Spot	195	1100
Futures	7066	7797
Options	830	502

Table 3.9: Traded volume of carbon products on EUA, CER and ERU in Mt. - Data source: DEHSt, originally from Point Carbon.

Furthermore, the share of their traded volume are illustrated in Figure 3.8 below. The inner ring displays the share of traded volume in 2012, while the outer ring displays the share of traded volume in 2013. In both years, futures contracts take the most market share (85% in average) and are therefore most liquid. Therefore, EUA futures price is considered as the benchmark of carbon permits of EU ETS by the market participants.

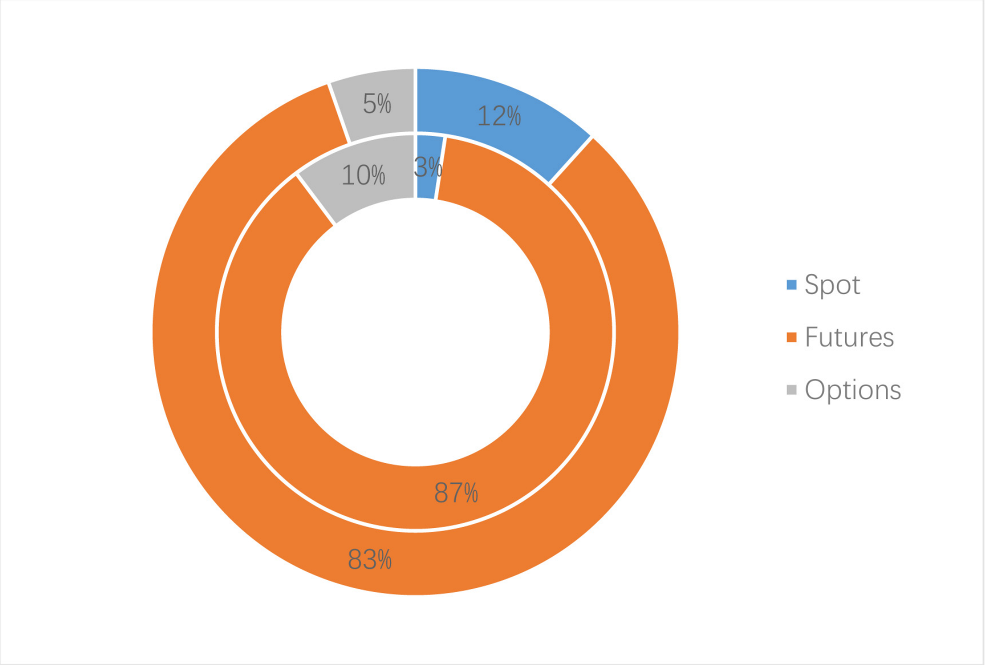


Figure 3.8: Share of traded volume in Mt. of 2012 (inner ring) and 2013 (outer ring) Data source: DEHSt, originally from Point Carbon.

As described in subsection 3.3.1, a futures contract on EUA is an agreement to buy or sell a tonne of emission allowance at a certain time in the future for a certain price on the ICE Futures Europe electronic platform. The most liquid contract is the futures contract with maturity in December of the same year. It expires always on the last Monday of the contract month. If the last Monday is a non-business day or there is a non-business day in the 4 days following the last Monday, the last day of trading will be the penultimate Monday of the delivery month. The settlement price is weighted average during the daily closing period from 16:50:00 - 16:59:59 hours of UK local time with quoted settlement prices if the liquidity is low. Figure 3.9 shows the front year futures prices with maturity in December and the corresponding traded volume from 22 April 2005 to 23 December 2016.

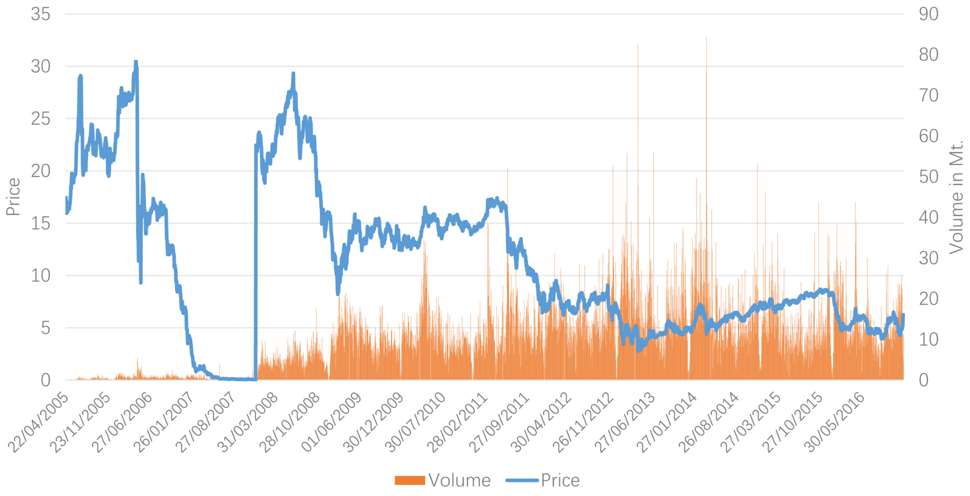


Figure 3.9: EUA front year futures contract prices and traded volume
Data source: ICE, Bloomberg.

Follows is the EUA price behavior and its background:

- The first price collapse was in the middle of 2006, when the first market assessment report of EU showed that EUA allowances were over-allocated. And the price decreased until the end of the first trading phase to only a few cents.
- Since the second trading phase, the price rose continuously as a result of more stringent caps set by the EU until Summer of 2008, then fell rapidly again due to the global financial and economic crisis.

- The price was relative stable thereafter for the next two years from middle 2009 to 2011, then rose slightly in March 2011. This was due to the nuclear disaster in Japan and consequently resulted in the political decision of Germany to shut down all nuclear plants, which increased the demand of fossil fuel worldwide and therefore also the demand of EUA allowances in EU.

- Thereafter, the price fell down rapidly again since middle 2011 due to the debt crisis in southern Europe and an increasing use of international credits of CERs and ERUs until the end of the second trading phase in December 2012.

- During the third trading phase since 2013, a series of political decisions was made to rebalance the market. The political decisions had a bullish effect on EUA prices not only from a fundamental but also from a sentimental aspect. Therefore, the EUA prices rose slightly again.

These political decisions mentioned above, including mainly the back-loading mechanism and the market stability reserve, will be specified in the subsequent section.

3.4 Reform of EU ETS and Outlook

The over-allocation of emission allowances in the EU ETS is a significant issue to be addressed, overwise it will undermine the market balance and lead a low carbon price. This caused the EUA price collapse in the first trading phase and low prices in the second and third trading phases. Although banking unused carbon permits is allowed since the second trading phase, a surplus of emission allowances built up within the system since the second trading phase, particularly since 2009 due to two main reasons.

- The the economic crisis in 2008 effected the production process EU-wide and therefore reduced the demand on EUAs.

- Without stringent restrictions, international credits were largely imported and resulted in a large band of emission allowances.

This resulted in a surplus amounted to around 2 billion allowances at the start of trading phase 3 and increased further to more than 2.1 billion in 2013. Therefore, various reform measures were adopted or still in plan to address the over-allocation problem.

3.4.1 Structure reform in phase 3

During trading phase 3, two main decisions were made by EU as short-term and long-term measure respectively.

As the short-term measure, a back-loading is implemented to postpone the auctioning of 900 million allowances until the end of the current trading phase from 2019 to 2020. The total auction volume is redistributed during phase 3. First, the auction volume from 2014 to 2016 has to be reduced annually by

- 400 million allowances in 2014;
- 300 million allowances in 2015; And
- 200 million allowances in 2016.

The postponed volume of allowances will be reinjected into the auction volume in 2019 and 2020 respectively. 300 million will be released in 2019 and then 600 million in 2020. The proposal of back-loading was implemented through an amendment to the EU ETS Auctioning Regulation in (EU 14b), which entered into force on 27 February 2014.

According to the Commission's impact assessment in (EC 14b), the purpose of implementation of back-loading is to rebalance the market supply and demand and also to reduce the price volatility in a short term. However, if 900 million allowances are reinjected into the auction volume from 2019 to 2020, it could cause a market over supply and increase the price volatility. Therefore, EC's proposal is to put this postponed volume into a reserve directly, so that it is not possible to effect the market balance to any extent. This reserve is called market stability reserve (MSR), and it is considered as a long-term measure to solve the allowance surplus issue.

As the long-term measure, the market stability reserve will be implemented by 2019 with aim to reduce the allowance auction volume in case of an allowance surplus for a long period. The MSR is also designed to improve the system's resilience to major shocks by adjusting the supply of allowances to be auctioned in the future, according to the impact assessment of EC in (EC 15b). Besides, unallocated allowances will also be transferred to the reserve. According to the estimation of EC in (EC 15b), there will be around 550 to 700 million allowances unallocated by 2020. Moreover, the MSR will also regulate the surplus volume on the market as of 2019. Follows are the key provisions of MSR summarized from the legislative proposal of the European Commission on this issue.

- The market stability reserve will be established in 2018 and the placing of allowances in the reserve will operate from 1 January 2019;
- The quantity of 900 million allowances deducted from auctioning volumes during the period 2014-2016, is not to be added to the volumes to be auctioned in 2019 and 2020. Instead, they will be placed in the MSR;
- Unallocated allowances during the trading period have also to be placed in the reserve in 2020;
- Each year, a number of allowances equal to 12% of the total number of allowances in surplus will be deducted from the auction volume, unless the number of allowances to be placed in the reserve would be less than 100 million.
- In 2019 for the reserve's operation, placements take place between 1 January and 1 September of the year of 8% (representing 1% for each calendar month) of the total number of allowances in surplus;
- In any year, if the total number of allowances in surplus is less than 400 million, 100 million allowances will be released from the reserve and added to the volume of allowances to be auctioned. If the allowances in the reserve are fewer than 100 million, all of them have to be released.

The legislative proposal of MSR is approved by the European Parliament and the Council in October 2015 in (EU 15). In the decision, the market surplus is defined as the total number of allowances in circulation (TNAC), which is calculated by the following formula:

$$\text{TNAC} = \text{Total Supply} - (\text{Total Demand} + \text{Allowances in the MSR}),$$

where the supply of emission allowances consists of the allowances banked from phase 2, the auctioned allowances, the allowances allocated for free and the allowances in the New Entrants Reserve, while the demand is determined by the emissions of the installations and the cancelled allowances.

3.4.2 Outlook for post 2020 phase

The emission reduction target of EU ETS in the post 2020 phase is bound with the objective of EU's 2030 climate and energy framework, which aims to reduce GHG emissions by at least 40% domestically below the 1990 level by 2030. To achieve the at least 40% target, all sectors covered by the ETS have to reduce their emissions by 43% compared to 2005. For this purpose the current linear reduction factor used to determine the cap has to be adjusted. Therefore, in July 2015 the European Commission presented a legislative proposal in (EC 15c) to revise the provisions of EU ETS for the period after 2020. The overall quantity of allowances will decline by 2.2% every year starting from 2021, instead of the original linear reduction factor (LRF) at 1.74%. According to EC, the additional emission reduction by this revise amounts to around 556 million tonnes from 2020 to 2030.

As the total number of allowances is declining, the total number of free allocation needs to be revised as well. EC also proposed to change the cross-sectoral correction factor (CSCF) to ensure the total allocation remains below the cap. According to the EC's proposal, the basic architecture will remain in place in the post 2020 period, while individual elements will be improved based on the benchmark values, the production data, the carbon leakage risk and the indirect carbon costs of the sectors and individual companies. In total, EC estimates that around 6.3 billion allowances to be allocated for free during this period.

Except for adjusting of LRF and CSCF, two support mechanisms are also planned to be set up to help the industry and the power sectors covered by the EU ETS. These are:

- The Innovation Fund. The Innovation Fund is to be established to support investments in renewable energy, carbon capture and storage (CCS) and low-carbon innovation in energy intensive industry. Around 450 million allowances are expected to be set aside to support the fund.
- The Modernisation Fund. The aim of the Modernisation Fund is to support lower income Member States of EU ETS in meeting the high investment needs relating to energy efficiency and the modernisation of their energy systems. Between 2021 and 2030, it is expected that around 310 million allowances in total could be set aside to establish the fund.

As the next step the legislative proposal for revising the EU ETS in the post 2020 period by EC is submitted to the European Parliament and to the Council for adoption, so that the proposal is able to enter into force.

4

Financial Modelling of EU ETS and its Derivative

Since the launch of the EU ETS in 2005, it keeps being the world's largest carbon market. The system is based on a cap-and-trade mechanism, which is considered to be cost efficient and effective to reduce emissions. Quantitative analysis on carbon permit prices are widely conducted and are useful for understanding the price behavior from the perspective of mathematical finance. This chapter will focus on the financial modelling of carbon permits of EU ETS. Existing pricing model will be discussed and new extended model will be investigated.

4.1 Background and Introduction

Before proceeding with the quantitative modelling, it is important to understand the purpose of choosing a cap-and-trade system. According to the theoretical arguments, a properly designed emission trading system based on the cap-and-trade mechanism will help to reduce the GHG emissions and achieve the low social costs. Such a mechanism works as follows: A central regulation authority determines the total quantity of emission allowances based on the historical emission data of all installations of the operators that covered by the system and allocates the corresponding amount of allowances to them. Each operator receives the allowances at the beginning of the compliance period and manages to have sufficient amount of allowances to cover its emissions polluted during the trading period and have to surrender them at the compliance deadline. If one operator fails to submit enough allowances by compliance, it has to face a penalty which applies for each tonne of uncovered eCO2. Since the cap has been set, no additional carbon permits can be created in the system. In case of lack of total emission allowances, operators have two options for their compliance. Either they can choose to reduce their emissions or to buy them from the market to avoid penalty. This helps to create the demand for allowances on the market and therefore determines a carbon price. Finally, the market will choose the most effective way for achieving this target. This means that the buyers are charged by purchasing allowances and the sellers are rewarded for improving their producing process and reducing their total emissions. In this way, the market finds the cheapest source for reduction target and achieves the lowest costs.

This mechanism can be illustrated by using a classic toy model. Assuming there are only two operators in the system and they are regulated by a central authority. The authority collects the emission data of the operators and calculates their emission reduction costs. It has the following data:

- Operator A emits 1000 tonnes of CO2 each year in average and will afford 20 Euro for its abatement costs, i.e., to pay 20 Euro for reducing one tonne of CO2.
- Operator B emits 1500 tonnes of CO2 each year and has to pay 10 Euro for its abatement costs.

Usually, the abatement costs can be expressed as a function of the reduction volume. The more emissions the operators choose to reduce, the lower they have to pay for each tonne of CO2 to be abated. And in theory, the carbon price is then determined as the marginal abatement costs. However, we do not consider a variable abatement cost in this toy model and simply assume a fixed abatement cost. Assuming that the authority decides to reduce the total emissions by 5% annually. Therefore, it allocates each operator 95% of their allowances they actually need and set a penalty level at 40 Euro. The authority has two options for its regulatory instrument to control the total emissions. It can either use the command and control regulation and obligates both operators

	Scenario 1: C&C system		**Scenario 2: C&T system**	
	Operator A	Operator B	Operator A	Operator B
Original emissions	1000 t	1500 t	1000 t	1500 t
Abatement costs	20 €	10 €	20 €	10 €
Reduction volume	50 t	75 t	0 t	125 t
Compliance costs	1000 €	750 €	750 €	500 €
Total social costs	1750 €		1250 €	

Table 4.1: Comparing individual and social abatement costs between command and control and cap-and-trade systems - The carbon permit price is set at 15 Euro.

to reduce their emissions by 5% each (scenario 1), or it can choose the cap-and-trade scheme by applying trading, so that emission allowances are able to be transferred between individual operators (scenario 2). In Table 4.1 we compare the individual and social costs from both options.

In the first scenario, both operators have to choose to reduce their emissions in order to avoid penalties, which are more expensive to them. Each operator faces its own abatement costs and this results a total reduction costs at 1750 Euro. In the second scenario by allowing tradable carbon permits, operators will behave differently. Operator A is willing to buy allowances at a price lower than 20 Euro, while Operator B is willing to sell the allowances at a price higher than 10 Euro. Therefore, operator B will choose to abate the total volume of emissions and sell the corresponding abatement volume to operator A. And an allowance price at any level between 10 and 20 would facilitate the transaction. Suppose in this case the carbon price would be 15 Euro, this results a total social costs of 1250 Euro. And each operator can realize compliance target at lower costs. In this sense, the market helps to achieve the abatement target in a cost efficient way. Studies on tradable permits would help to lead to deep understanding of emission trading mechanism.

In the EU ETS, besides EUA allowances on the spot market, futures and options on allowances are being traded and have more traded volume on the secondary market, see Figure 3.6 and Figure 3.8. Various authors have discussed the design of the market and the pricing of the permits and the derivatives traded. The fundamental concepts for emission trading and the market mechanism have been reviewed in the paper of Taschini in (Tasc 09), which also provides a literature overview. Equilibrium models for allowance permit markets have been widely used to capture the theoretical properties of emission trading schemes. Examples are the dynamic but deterministic model proposed by Rubin in (Rubi 96) and stochastic equilibrium approaches such as Seifert et al. in (SeUW 08), Wagner in (Wagn 06) and Carmona et al. in (CaFH 09). These models use optimal stochastic control to investigate the dynamic emission trading in the risk-neutral framework. Carmona et al. (CFHP 10) derive the permit price formula which can be described as the discounted penalty multiplied by the probability of the excess demand event. Its historical model fit has been evaluated by Grüll and Taschini in (GruT 09). Carmona and Hinz in (CarH 11) and Hinz in (Hinz 10) propose a reduced-form model which is particular feasible for the calibration of EUA futures and options as it directly models the underlying price process. Both Paolella and Taschini (PaoT 08) and Benz and Trück (BenT 09) provide an econometric analysis for the short-term spot price behavior and the heteroscedastic dynamics of the price returns. For the option pricing, Carmona and Hinz in (CarH 11) derive a option pricing formula from their reduced-form model for a single trading period. They also discuss the extension of the formula to two trading periods. Hitzemann and Uhrig-Homburg in (HitU 11a) and (HitU 11b) develop an option pricing model for multi-compliance periods by considering a remaining value component in the pricing formula capturing the expected value after a finite number of trading periods.

As emission certificates are traded assets, their price paths carry information on the market participant expectations on the development of the fundamental price drivers of the certificates including the regulatory framework. In particular, prices of futures and options of certificates carry forward-looking information which can be extracted by using appropriate valuation models. In this chapter we derive such a model by extending the reduced-form pricing model of Carmona and Hinz in (CarH 11). Using an extensive data set we extract a time series for the implied market price of risk, which relates to the risk premium the investors attach to the certificates. This requires a calibration of the model to historical price data during varying time periods and with different maturities of futures and options. A crucial step in the calibration procedure is a price transformation of normalized futures prices of permits from a pricing measure to the historical measure. We find that the implied market price of risk possesses stochastic characteristics. Therefore, we extend the existing reduced-form model by modelling the dynamics of the market price of risk as an Ornstein-Uhlenbeck process and show that the extended model captures the appropriate properties of the market. The market price of risk is an implied value related to the permit prices, this requires an extension of the univariate permit pricing model to a bivariate one. In this context, the standard Kalman filter algorithm is considered to be an effective way to calibrate to the historical prices. We apply this methodology and estimate the implied risk premia. Once the risk premia have been determined, EUA option prices can be derived to fit the bivariate model setting, which helps to improve the accuracy of pricing.

This chapter is organized as follows. In section 2, a basic reduced-form model of Carmona and Hinz in (CarH 11) based on a risk-neutral framework will be introduced. The model with an extended data series will be calibrated and the calibration results will be analyzed. In section 3 an extended bivariate pricing model will be investigated in order to capture the market information of the risk premia. By demonstrating how to calibrate the extended model by applying the standard Kalman filter algorithm, the estimation results of this procedure will be presented and the model fit will be discussed. In section 4, the option pricing performance will be evaluated by taking into account the calibration results of the bivariate model.

4.2 Univariate EUA Pricing Model and Parameter Estimation

4.2.1 Univariate model

We consider an emission trading scheme with a single trading phase with horizon $[0, T]$. The price evolution of emission permits is assumed to be adapted stochastic processes on a filtered probability space $(\Omega, \mathcal{F}, (\mathcal{F}_t)_{t\in[0,T]}, \mathbb{P})$ with an equivalent risk-neutral measure $\mathbb{Q} \sim \mathbb{P}$. Based on the assumption of a market compliance at time T the price has only two possible outcomes, namely zero or the penalty level. The argument is as follows. If there are sufficient emission allowances in the market to cover the total emissions at compliance time, surplus allowances will become worthless. Otherwise, for undersupplied permits the price will increase to the penalty level.

The reduced-form model of Carmona and Hinz (CarH 11) will be introduced as follows. Consider the price process of a EUA futures contract $(A_t)_{t\in[0,T]}$ with maturity data T written on the allowance price. $N \subset \mathcal{F}_T$ denotes the non-compliance event which settles the $\{0,p\}$-dichotomy of the terminal futures price by $A_T = p1_N$, where p is the penalty level. Let $(\Gamma_t)_{t\in[0,T]}$ be the aggregated normalized emission, then the non-compliance event is denoted by:

$$N = (\Gamma_T) \geq 1.$$

Therefore, under the equivalent martingale measure $\mathbb{Q}$ one has

$$A_t = p\,\mathbb{E}^{\mathbb{Q}}[1_N|\mathcal{F}_t] = p\,\mathbb{E}^{\mathbb{Q}}[1_{\{\Gamma_T\geq 1\}}|\mathcal{F}_t], \quad t \in [0,T].$$

To simplify the notation, one considers the normalized futures price process $(a_t)_{t\in[0,T]}$ given by

$$a_t = \frac{1}{p}A_t = \mathbb{E}^{\mathbb{Q}}[1_{\{\Gamma_T\geq 1\}}|\mathcal{F}_t], \quad t \in [0,T]. \tag{4.1}$$

Furthermore, by using the notation $\mathcal{N}(\mu,\sigma^2)$ for the normal distribution with mean μ and variance σ^2, and using Φ for the cumulative distribution function of the standard normal distribution, one receives the following proposition.

Proposition 4.2.1. *Let the process $(\Gamma_t)_{t\in[0,T]}$ denote the aggregated normalized emission, and is assumed to follow a lognormal process given by*

$$\Gamma_t = \Gamma_0 e^{\int_0^t \sigma_s d\widetilde{W}_s - \frac{1}{2}\int_0^t \sigma_s^2 ds}, \quad \Gamma_0 \in (0,\infty),$$

where σ_t stands for the volatility of the emission pollution rate. $t \hookrightarrow \sigma_t$ is a deterministic function which is continuous and square-integrable. $(\widetilde{W}_t)_{t\in[0,T]}$ is a Brownian motion with respect to $\mathbb{Q}$. Then the martingale

$$a_t = \mathbb{E}^{\mathbb{Q}}[1_{\{\Gamma_T\geq 1\}}|\mathcal{F}_t], \quad t \in [0,T]$$

is given by

$$a_t = \Phi\left(\frac{\Phi^{-1}(a_0)\sqrt{\int_0^T \sigma_s^2 ds} + \int_0^t \sigma_s d\widetilde{W}_s}{\sqrt{\int_t^T \sigma_s^2 ds}}\right), \tag{4.2}$$

and it solves the stochastic differential equation (SDE)

$$da_t = \Phi'(\Phi^{-1}(a_t))\sqrt{z_t}d\widetilde{W}_t, \tag{4.3}$$

with the function $t \hookrightarrow z_t$, $t \in (0, T)$, given by

$$z_t = \frac{\sigma_t^2}{\int_t^T \sigma_u^2 du}. \tag{4.4}$$

However, the author only provides a proof idea for the proposition in the original paper. A complete proof is given as follows.

Proof. First one has

$$\begin{aligned}
a_t &= \mathbb{E}^{\mathbb{Q}}[1_{\{\Gamma_T \geq 1\}}|\mathcal{F}_t] = \mathbb{Q}\{\Gamma_T \geq 1|\mathcal{F}_t\} \\
&= \mathbb{Q}\left\{\Gamma_t e^{\int_t^T \sigma_s d\widetilde{W}s - \frac{1}{2}\int_t^T \sigma_s^2 ds} \geq 1|\mathcal{F}_t\right\} \\
&= \mathbb{Q}\left\{\ln\Gamma_t + \int_t^T \sigma_s d\widetilde{W}s - \frac{1}{2}\int_t^T \sigma_s^2 ds \geq 0|\mathcal{F}_t\right\} \\
&= \mathbb{Q}\left\{\int_t^T \sigma_s d\widetilde{W}s \geq -\ln\Gamma_t + \frac{1}{2}\int_t^T \sigma_s^2 ds|\mathcal{F}_t\right\} \\
&= \mathbb{Q}\left\{\hat{\mathcal{N}} \geq -\ln\Gamma_t + \frac{1}{2}\int_t^T \sigma_s^2 ds|\mathcal{F}_t\right\} \quad \text{where} \quad \hat{\mathcal{N}} \sim \left(0, \int_t^T \sigma_s^2 ds\right) \\
&= \mathbb{Q}\left\{\hat{\mathcal{N}} \leq \ln\Gamma_t - \frac{1}{2}\int_t^T \sigma_s^2 ds|\mathcal{F}_t\right\} \\
&= \mathbb{Q}\left\{\hat{\mathcal{N}} \leq \ln\Gamma_t - \frac{1}{2}\int_t^T \sigma_s^2 ds\right\}.
\end{aligned}$$

Note that $\hat{\mathcal{N}}$ is normally distributed, the equation above becomes

$$\begin{aligned}
a_t &= \Phi\left(\frac{\ln\Gamma_t - \frac{1}{2}\int_t^T \sigma_s^2 ds}{\sqrt{\int_t^T \sigma_s^2 ds}}\right) \\
&= \Phi\left(\frac{\ln(\Gamma_0 e^{\int_0^t \sigma_s d\widetilde{W}_s - \frac{1}{2}\int_0^t \sigma_s^2 ds}) - \frac{1}{2}\int_t^T \sigma_s^2 ds}{\sqrt{\int_t^T \sigma_s^2 ds}}\right) \\
&= \Phi\left(\frac{\ln\Gamma_0 + \int_0^t \sigma_s d\widetilde{W}_s - \frac{1}{2}\int_0^T \sigma_s^2 ds}{\sqrt{\int_t^T \sigma_s^2 ds}}\right) \\
&= \Phi\left(\frac{\ln\Gamma_0 - \frac{1}{2}\int_0^T \sigma_s^2 ds}{\sqrt{\int_0^T \sigma_s^2 ds}} \, \frac{\sqrt{\int_0^T \sigma_s^2 ds}}{\sqrt{\int_t^T \sigma_s^2 ds}} + \frac{\int_0^t \sigma_s d\widetilde{W}_s}{\sqrt{\int_t^T \sigma_s^2 ds}}\right).
\end{aligned}$$

Now taking into account the initial condition of a_t in the last equation:

$$a_0 = \Phi\left(\frac{\ln\Gamma_0 - \frac{1}{2}\int_0^T \sigma_s^2 ds}{\sqrt{\int_0^T \sigma_s^2 ds}}\right),$$

(4.2) can be obtained. To show (4.3), define

$$a_t = \Phi(\xi_t), t \in [0, T]. \tag{4.5}$$

One has

$$\begin{aligned}
\xi_t &= \frac{\ln\Gamma_t - \frac{1}{2}\int_t^T \sigma_s^2 ds}{\sqrt{\int_t^T \sigma_s^2 ds}} = \frac{\ln\Gamma_0 - \frac{1}{2}\int_0^T \sigma_s^2 ds + \int_0^t \sigma_s d\widetilde{W}_s}{\sqrt{\int_t^T \sigma_s^2 ds}} \\
&= \ln\Gamma_0\left(\int_t^T \sigma_s^2 ds\right)^{-\frac{1}{2}} - \frac{1}{2}\int_0^T \sigma_s^2 ds\left(\int_t^T \sigma_s^2 ds\right)^{-\frac{1}{2}} + \int_0^t \sigma_s d\widetilde{W}_s\left(\int_t^T \sigma_s^2 ds\right)^{-\frac{1}{2}}.
\end{aligned}$$

Therefore, by computing the Itô differential, one obtains

$$\begin{aligned}
d\xi_t =& -\frac{1}{2}\ln\Gamma_0\left(\int_t^T \sigma_s^2 ds\right)^{-\frac{3}{2}}(-\sigma_t^2)dt - \frac{1}{2}\left(-\frac{1}{2}\right)\int_0^T \sigma_s^2 ds\left(\int_t^T \sigma_s^2 ds\right)^{-\frac{3}{2}}(-\sigma_t^2)dt \\
&- \frac{1}{2}\int_0^t \sigma_s d\widetilde{W}_s\left(\int_t^T \sigma_s^2 ds\right)^{-\frac{3}{2}}(-\sigma_t^2)dt + \left(\int_t^T \sigma_s^2 ds\right)^{-\frac{1}{2}}\sigma_t \widetilde{W}_t dt \\
=& \frac{1}{2}\frac{\ln\Gamma_t - \frac{1}{2}\int_t^T \sigma_s^2 ds}{\sqrt{\int_t^T \sigma_s^2 ds}}\left(\int_t^T \sigma_s^2 ds\right)^{-1}\sigma_t^2 dt + \left(\int_t^T \sigma_s^2 ds\right)^{-\frac{1}{2}}\sigma_t d\widetilde{W}_t \\
=& \left(\int_t^T \sigma_s^2 ds\right)^{-\frac{1}{2}}\sigma_t d\widetilde{W}_t + \frac{1}{2}\xi_t\left(\int_t^T \sigma_s^2 ds\right)^{-1}\sigma_t^2 dt \\
=& \sqrt{z_t} d\widetilde{W}_t + \frac{1}{2} z_t \xi_t dt,
\end{aligned}$$

with the quadratic variation $d[\xi_t] = (d\xi_t)^2 = z_t dt$. Now by applying the Itô's formula, one can derive the differential of the normalized futures price as

$$\begin{aligned}
da_t &= \Phi'(\xi_t)d\xi_t + \frac{1}{2}\Phi''(\xi_t)(d\xi_t)^2 \\
&= \Phi'(\xi_t)\left(\sqrt{z_t}d\widetilde{W}_t + \frac{1}{2}z_t\xi_t dt\right) + \frac{1}{2}\Phi''(\xi_t)(d\xi_t)^2 \\
&= \frac{1}{2}(\Phi'(\xi_t)\xi_t + \Phi''(\xi_t))z_t dt + \Phi'(\xi_t)\sqrt{z_t}d\widetilde{W}_t \\
&= \Phi'(\xi_t)\sqrt{z_t}d\widetilde{W}_t \\
&= \Phi'(\Phi^{-1}(a_t))\sqrt{z_t}d\widetilde{W}_t,
\end{aligned}$$

since $\Phi(x)$ is a monotonically increasing function. The penultimate equation is satisfied by using the result $\Phi'(x)x + \Phi''(x) = 0$. Actually, we have

$$\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{s^2}{2}} ds \quad \Rightarrow \quad \Phi(x)' = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}$$

$$\Rightarrow \quad \Phi(x)'' = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}(-x) \quad \Rightarrow \quad \Phi'(x)x + \Phi''(x) = 0.$$

□

In order to calibrate the model, Carmona and Hinz (CarH 11) suggest to use the function

$$z_t = \beta(T-t)^{-\alpha},$$

with $\alpha \in \mathbb{R}$ and $\beta \in (0, \infty)$, so one has

$$da_t = \Phi'(\Phi(a_t))\sqrt{\beta(T-t)^{-\alpha}}\, d\widetilde{W}_t. \tag{4.6}$$

To estimate the parameters one has to determine the distribution of the price variable. For this purpose one considers the price transformation process ξ_t defined by $a_t = \Phi(\xi_t)$ in (4.5). By applying Itô's formula one has

$$d\xi_t = \left(\frac{1}{2} z_t \xi_t + \sqrt{z_t} h\right) dt + \sqrt{z_t}\, dW_t, \tag{4.7}$$

where W_t denotes the Brownian motion under the objective measure $\mathbb{P}$ and h is the market price of risk which is assumed to be constant. Now consider two different time points t and τ with $0 < t < \tau < T$. From the expression of ξ_t in the proof above it is easy to see that ξ_τ can be given explicitly as a function of ξ_t:

$$\xi_\tau = e^{\frac{1}{2}\int_t^\tau z_s ds} \xi_t + \int_t^\tau e^{\frac{1}{2}\int_s^\tau z_u du} \sqrt{z_s}\, d\widetilde{W}_s. \tag{4.8}$$

Then one receives the following proposition.

Proposition 4.2.2. *Under the objective measure $\mathbb{P}$ equation (4.8) reads*

$$\xi_\tau = e^{\frac{1}{2}\int_t^\tau z_s ds} \xi_t + h \int_t^\tau e^{\frac{1}{2}\int_s^\tau z_u du} \sqrt{z_s}\, ds + \int_t^\tau e^{\frac{1}{2}\int_s^\tau z_u du} \sqrt{z_s}\, dW_s. \tag{4.9}$$

Proof. Generally, the price transformation ξ_t has the dynamics given by

$$d\xi_t = (\frac{1}{2}z_t\xi_t + \sqrt{z_t}\lambda_t)dt + \sqrt{z_t}dW_t,$$

with a time-varying market price of risk λ_t. In order to solve the Stochastic differential equation, consider the functions defined by

$$g(t) = e^{-\frac{1}{2}\int_0^t z_s ds}, \qquad f(t, \xi_t) = \xi_t g(t).$$

By applying Itô's formula one obtains

$$\begin{aligned} df(t, \xi_t) &= g'(t)\xi_t dt + g(t)d\xi_t \\ &= -\frac{1}{2}z_t g(t)\xi_t dt + g(t)(\frac{1}{2}z_t\xi_t + \lambda_t\sqrt{z_t})dt + g(t)\sqrt{z_t}dW_t \\ &= g(t)\lambda_t\sqrt{z_t}dt + g(t)\sqrt{z_t}dW_t. \end{aligned}$$

Thus the left hand side of the function $f(t, \xi_t)$ can be written as the integral form

$$\begin{aligned} f(t, \xi_t) &= f(0, \xi_0) + \int_0^t g(s)\lambda_t\sqrt{z_s}ds + \int_0^t g(u)\sqrt{z_u}dW_u \\ &= \xi_0 g(0) + \int_0^t g(s)\lambda_t\sqrt{z_s}ds + \int_0^t g(u)\sqrt{z_u}dW_u. \end{aligned}$$

Note that at $t = 0$, $g(0) = 1$. The right hand side of the function $f(t, \xi_t)$ equals

$$\xi_t g(t) = \xi_t e^{-\frac{1}{2}\int_0^t z_s ds} = \xi_0 + \int_0^t e^{-\frac{1}{2}\int_0^s z_{s'}ds'}\lambda_t\sqrt{z_s}ds + \int_0^t e^{-\frac{1}{2}\int_0^u z_{u'}du'}\sqrt{z_u}dW_u.$$

Then the SDE of ξ_t can be solved as

$$\begin{aligned} \xi_t &= \xi_0 e^{\frac{1}{2}\int_0^t z_s ds} + \int_0^t e^{\frac{1}{2}\int_0^t z_{s'}ds'} e^{\frac{1}{2}\int_s^0 z_{s'}ds'}\lambda_t\sqrt{z_s}ds + \int_0^t e^{\frac{1}{2}\int_0^t z_{u'}du'} e^{\frac{1}{2}\int_u^0 z_{u'}du'}\sqrt{z_u}dW_u \\ &= \xi_0 e^{\frac{1}{2}\int_0^t z_s ds} + \int_0^t e^{\frac{1}{2}\int_s^t z_{s'}ds'}\lambda_t\sqrt{z_s}ds + \int_0^t e^{\frac{1}{2}\int_u^t z_{u'}du'}\sqrt{z_u}dW_u \\ &= \xi_0 e^{\frac{1}{2}\int_0^t z_s ds} + \int_0^t e^{\frac{1}{2}\int_s^t z_{s'}ds'}\lambda_t\sqrt{z_s}ds + \int_0^t e^{\frac{1}{2}\int_s^t z_{s'}ds'}\sqrt{z_s}dW_s, \end{aligned}$$

which means that for any given τ with $0 \leq t \leq \tau \leq T$, ξ_τ has the solution

$$\xi_\tau = \xi_t e^{\frac{1}{2}\int_t^\tau z_s ds} + \int_t^\tau e^{\frac{1}{2}\int_s^\tau z_{s'}ds'}\lambda_t\sqrt{z_s}ds + \int_t^\tau e^{\frac{1}{2}\int_s^\tau z_{s'}ds'}\sqrt{z_s}dW_s.$$

The proposition is then proved by taking a constant λ_t.

$\square$

Consequently, for each $i = 1, 2, ..., n$, the conditional distribution of ξ_{t_i} given $\xi_{t_{i-1}}$ is Gaussian with mean μ_i and variance σ_i^2 given by

$$\mu_i = e^{\frac{1}{2}\int_{t_{i-1}}^{t_i} z_s ds}\xi_{t_{i-1}} + h\int_{t_{i-1}}^{t_i} e^{\frac{1}{2}\int_s^{t_i} z_u du}\sqrt{z_s}ds,$$

$$\sigma_i^2 = \int_{t_{i-1}}^{t_i} z_s e^{\int_s^{t_i} z_u du}ds.$$

Now ξ_t is conditional Gaussian so that its log-likelihood can be calculated and the Maximum-likelihood estimation can be applied to find the model parameters.

4.2.2 Estimation

Suppose μ_i and σ_i^2 are functions of the variables h, α, β mentioned in the previous subsection. By using the following integral approximations, parameters of the log-likelihood can be calculated numerically:

$$\mu_i \sim e^{\frac{1}{2}(t_i - t_{i-1})z_{t_{i-1}}}\xi_{t_{i-1}} + h(t_i - t_{i-1})e^{\frac{1}{2}(t_i - t_{i-1})z_{t_{i-1}}}\sqrt{z_{t_{i-1}}},$$

$$\sigma_i^2 \sim (t_i - t_{i-1})z_{t_{i-1}}e^{(t_i - t_{i-1})z_{t_{i-1}}},$$

with $z_{t_i} = \beta(T - t_i)^{-\alpha}$, $i = 1, 2, ..., n$. One can calibrate the model to different emission trading periods during the first and second EU ETS trading phases. Consider the daily prices of the EUA futures with maturities in December from 2005 to 2012. Their historical price series are shown in Figure 4.1.

The price transformation ξ_t is conditional Gaussian with its mean μ_t and variance σ_t^2. We consider the daily historical observations of the EUA futures at time $t_1, t_2, ...t_n$. Their corresponding price transformations can be determined by using the definition $a_t = \Phi(\xi_t)$. Thus the parameters α, β, h can be estimated by maximizing the log-likelihood function given by

$$L_{\xi_{t_i},...,\xi_{t_n}}(h, \alpha, \beta) = \sum_{i=1}^{n}\left(-\frac{(\xi_{t_i} - \mu_i(h, \alpha, \beta))^2}{2\sigma_i^2(\alpha, \beta)} - \ln\left(\sqrt{2\pi\sigma_i^2(\alpha, \beta)}\right)\right). \quad (4.10)$$

Under the model assumptions the residuals

$$w_i = \frac{\xi_{t_i} - \mu_i(h, \alpha, \beta)}{\sqrt{\sigma_i^2(\alpha, \beta)}}, \quad i = 1, ..., n, \quad (4.11)$$

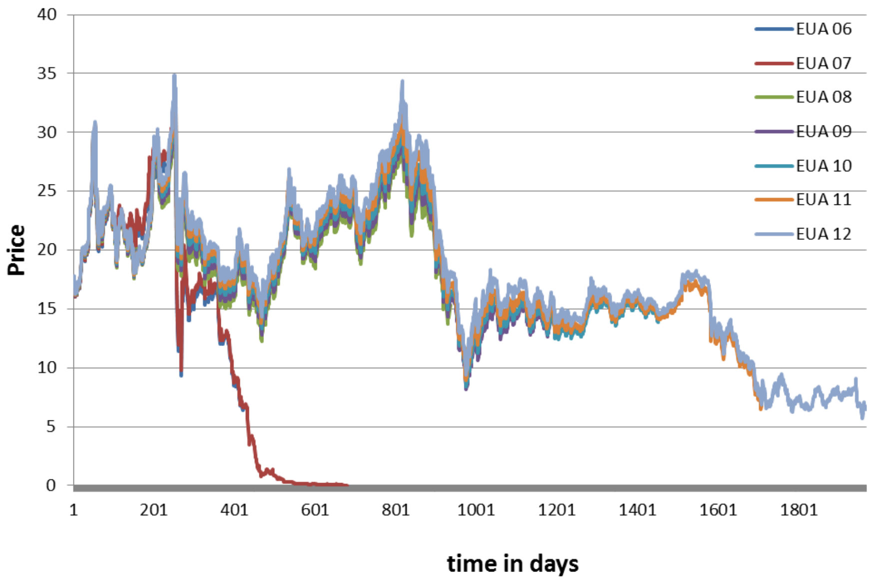


Figure 4.1: Historical prices of the EUA futures with maturities in December from 2005 to 2012

must be a series of independent standard normal random variables. So standard statistical analysis can be applied to test the quality of the model fit. The estimation results are shown in Table 4.2. The horizons of the price data are two years, starting from the first trading day in January of the previous trading year to the last trading day in December of the next year.

Comparing the estimation values in Table 4.2, the instability of the parameter values in each cell for different time periods can be observed. Note the value for the market price of risk changes its sign during the first and second trading phase. This implies the inappropriateness of the assumption for a constant market price of risk. The fourth value in each cell is the negative of LLF. Note the -LLF are much lower after the first trading phase because the price collapse during 2006 to 2007 partially affects the data.

In Figure 4.2 to Figure 4.6 we display the time series of the residuals w_i, their empirical auto-correlations, empirical partial auto-correlations and quantile-quantile-plots. The EUA futures with maturity in December 2007 (EUA 07) and EUA futures with maturity in December 2012 (EUA 12) are chosen as examples.

The time series w_i show an effect of volatility clustering. This is confirmed by significant values to high lags in the sample autocorrelation and sample partial autocorrelation. Also the Q-Q plots, especially for the first trading phase, indicate heavy tails and a non-Gaussian behavior. A formal analysis with an application of Jarque-Bera test rejects the hypothesis that the data set is generated from normally distributed random variables. In order to improve the model fit, we extend the model by introduction of a dynamic market price of risk in the subsequent section.

maturity\time period.	Apr.05-Dec.06	Jan.06-Dec.07	Jan.07-Dec.08	Jan.08-Dec.09	Jan.09-Dec.10	Jan.10-Dec.11	Jan.11-Dec.12
Dec.06	-0.3501 0.7818 0.7470 -644.5836						
Dec.07	-0.4303 0.5556 0.6002 -646.0240	0.1326 0.7599 1.3959 -739.0301					
Dec.08	-0.8022 0.0632 -0.1473 -989.4653	-1.9960 0.0260 -0.3918 -1276.0276	0.0870 0.0751 0.0551 -1324.2164				
Dec.09	-0.8995 0.0438 -0.2260 -984.3740	-3.2116 0.0028 -0.4051 -1279.0503	0.0191 0.0748 0.0899 -1358.3749	-0.2602 0.0811 0.4049 -1312.4067			
Dec.10	-1.1852 0.0221 -0.2480 -986.8374	-4.3385 0.0002 -0.4157 -1281.3926	0.0104 0.0750 0.0896 -1357.4328	-0.3174 0.0645 0.6054 -1331.5990	-0.7881 0.0544 0.2404 -1455.5480		
Dec.11	-1.3765 0.0129 -0.2729 -978.9760	-5.7102 0.0001 -0.4358 -1279.6562	0.0579 0.0791 0.0834 -1361.8570	-0.4098 0.0506 0.5952 -1332.8319	-2.2939 0.0092 0.1349 -1497.0551	0.4460 0.0331 0.4657 -1528.8444	
Dec.12	-1.6486 0.0062 -0.2951 -976.2664	-6.8341 0.0000 -0.4138 -1273.2228	0.0277 0.0782 0.0611 -1355.5116	-0.5419 0.0373 0.5816 -1332.0014	-3.5805 0.0008 0.1823 -1500.6628	1.4572 0.1090 0.4183 -1524.7310	0.1279 0.0680 0.6948 -1355.8639

Table 4.2: Parameter estimate results of Univariate Model - In each cell the first value stands for α, second for β, third for the market price of risk (MPR) h, the last one for the negative of LLF. Note that from 2005 to 2007 is the first trading phase, from 2008 to 2012 is the second trading phase.

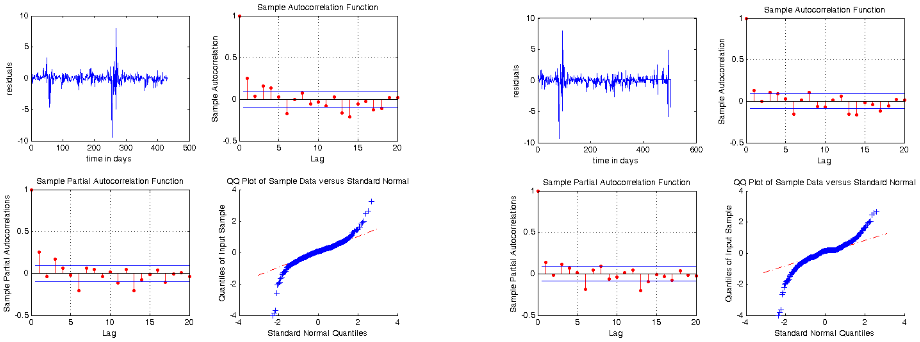


Figure 4.2: Statistical analysis of EUA 07, time period 05-06 and 06-07.

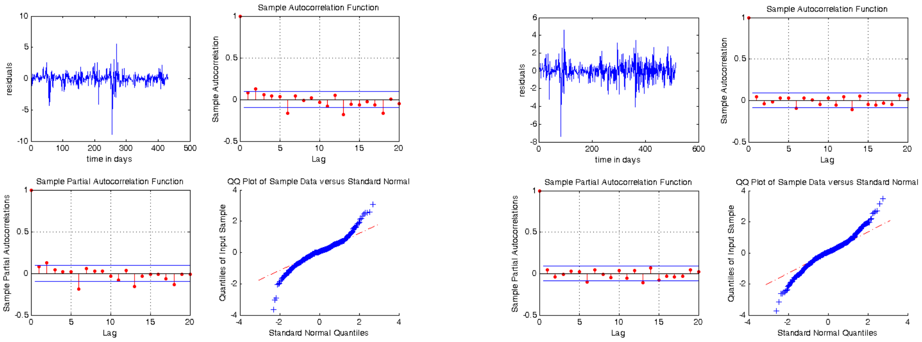


Figure 4.3: Statistical analysis of EUA 12, time period 05-06 and 06-07.

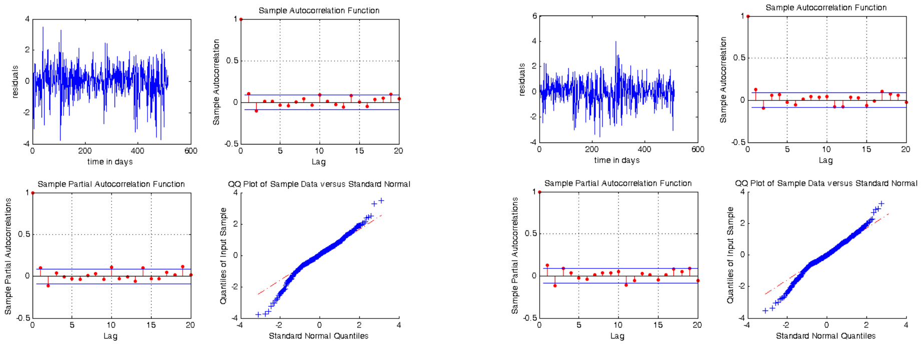


Figure 4.4: Statistical analysis of EUA 12, time period 07-08 and 08-09.

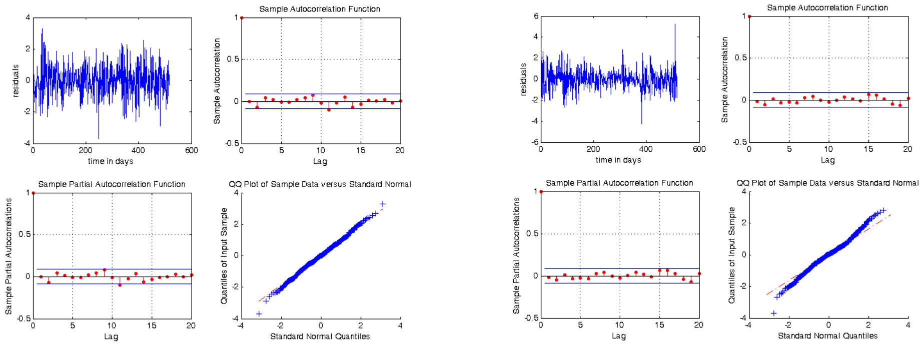


Figure 4.5: Statistical analysis of EUA 12, time period 09-10 and 10-11.

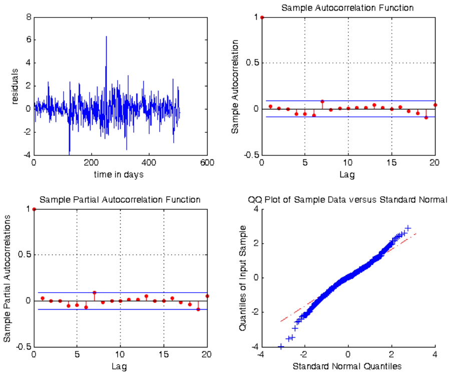


Figure 4.6: Statistical analysis of EUA 12, time period 11-12.

4.3 Bivariate Pricing Model for EUA

4.3.1 Model description

In order to illustrate the dynamic property of the market price of risk we consider a bivariate permit pricing model in this section. We model the market price of risk as an Ornstein-Uhlenbeck process as its value can be either positive or negative and denote it by λ_t. Recall the equation for the normalized price process under the risk-neutral measure $\mathbb{Q}$ given by (4.3). According to Girsanov's theorem, the bivariate pricing model under the objective measure $\mathbb{P}$ is given by

$$\begin{aligned} da_t &= \Phi'(\Phi^{-1}(a_t))\sqrt{z_t}(\lambda_t dt + dW_t^1), \\ d\lambda_t &= \theta(\bar{\lambda} - \lambda_t)dt + \sigma_\lambda dW_t^2, \\ dW_t^1 dW_t^2 &= \rho dt. \end{aligned}$$

where W_t^1 and W_t^2 are two one-dimensional Brownian motions with correlation coefficient ρ. Note that under the model assumptions, the filtration $(\mathcal{F}_t)$ in the probability space must be assumed to be generated by the bivariate Brownian motion.

The use of Girsanov's theorem in the bivariate model requires the condition that the process Z_t given by

$$Z_t = \exp\Big(\int_0^t \lambda_s dW_s - \frac{1}{2}\int_0^t \lambda_s^2 ds\Big) \tag{4.12}$$

is a martingale. The following proposition can be proved.

Proposition 4.3.1. *Under the model assumptions, the process Z_t given by (4.12) is a martingale.*

Proof. In order to show the martingale property in (4.12), it is sufficient to prove the Novikov's condition given by

$$\mathbb{E}\Big[\exp\Big(\frac{1}{2}\int_0^T \lambda_s^2 ds\Big)\Big] < \infty.$$

In the bivariate EUA pricing model, where λ_t follows a Ornstein-Uhlenbeck-Proces given by

$$d\lambda_t = \theta(\bar{\lambda} - \lambda_t)dt + \sigma_\lambda dWt,$$

this condition is always satisfied. We first show that there exists a constant $\epsilon > 0$ such that for any $S \in [0, T]$, we have

$$\mathbb{E}\Big[\exp\Big(\frac{1}{2}\int_S^{S+\epsilon} \lambda_t^2 dt\Big)\Big] < \infty. \tag{4.13}$$

To show (4.13) we consider the term in the expectation notation. By applying Jensen's inequality we have

$$\exp\Big(\frac{1}{2}\int_S^{S+\epsilon} \lambda_t^2 dt\Big) = \exp\Big(\int_S^{S+\epsilon} \frac{1}{\epsilon}\frac{\epsilon}{2}\lambda_t^2 dt\Big)$$
$$= \exp\Big(\frac{1}{\epsilon}\int_S^{S+\epsilon} \frac{\epsilon}{2}\lambda_t^2 dt\Big) \leq \frac{1}{\epsilon}\int_S^{S+\epsilon} \exp\Big(\frac{\epsilon}{2}\lambda_t^2\Big) dt.$$

By applying Fubini's theorem (4.13) becomes

$$\frac{1}{\epsilon}\int_S^{S+\epsilon} \mathbb{E}\Big[\exp\Big(\frac{\epsilon}{2}\lambda_t^2\Big)\Big] dt. \tag{4.14}$$

The process λ_t is a Gaussian process with mean and variance given by

$$\mathbb{E}[\lambda_t] = \mu_t = \lambda_0 e^{-\theta t} + \bar{\lambda}(1 - e^{-\theta t}),$$
$$\mathrm{Var}(\lambda_t) = \sigma_t^2 = \frac{\sigma_\lambda^2}{2\theta}(1 - e^{-2\theta t}).$$

We have $\lambda_t \sim \mathcal{N}(\mu_t, \sigma_t^2)$. Now let Z be a standard normal-distributed random variable $Z \sim \mathcal{N}(0, 1)$. So in (4.14) we have

$$\begin{aligned}\mathbb{E}\Big[\exp\Big(\frac{\epsilon}{2}\lambda_t^2\Big)\Big] &= \mathbb{E}\Big[\exp\Big(\frac{\epsilon}{2}(\mu_t + \sigma_t Z)^2\Big)\Big] \\ &= \mathbb{E}\Big[\exp\Big(\frac{\epsilon\mu_t^2}{2} + \epsilon\mu_t\sigma_t Z + \frac{\epsilon\sigma_t^2 Z^2}{2}\Big)\Big] \\ &= \int_{\mathbb{R}} \exp\Big(\frac{\epsilon\mu_t^2}{2} + \epsilon\mu_t\sigma_t x + \frac{\epsilon\sigma_t^2 x^2}{2}\Big)\frac{1}{\sqrt{2\pi}}\exp\Big(-\frac{x^2}{2}\Big) dx \\ &= \exp\Big(\frac{\epsilon\mu_t^2}{2}\Big)\int_{\mathbb{R}} \frac{1}{\sqrt{2\pi}}\exp\Big(-\frac{1 - \epsilon\sigma_t^2}{2}x^2 + \epsilon\mu_t\sigma_t x\Big) dx.\end{aligned}$$

To calculate the integration term above, let $a_t = 1 - \epsilon\sigma_t^2$ and $b_t = \epsilon\mu_t\sigma_t$, and make the integral-substitution. Then we have

$$\begin{aligned}
&\int_{\mathbb{R}} \frac{1}{\sqrt{2\pi}} \exp\Big(-\frac{1-\epsilon\sigma_t^2}{2}x^2 + \epsilon\mu_t\sigma_t x\Big)dx \\
=&\int_{\mathbb{R}} \frac{1}{\sqrt{2\pi}} \exp\Big(-\frac{1}{2}(a_t x^2 - 2b_t x)\Big)dx \\
=&\int_{\mathbb{R}} \frac{1}{\sqrt{2\pi}} \exp\Big(-\frac{1}{2}\Big(y^2 - 2b_t\frac{1}{\sqrt{a_t}}y\Big)\Big)\frac{1}{\sqrt{a_t}}dy \\
=&\frac{1}{\sqrt{a_t}}\int_{\mathbb{R}} \frac{1}{\sqrt{2\pi}} \exp\Big(-\frac{1}{2}\Big(y^2 - \frac{2b_t}{\sqrt{a_t}}y + \Big(\frac{b_t}{\sqrt{a_t}}\Big)^2 - \Big(\frac{b_t}{\sqrt{a_t}}\Big)^2\Big)\Big)dy \\
=&\frac{1}{\sqrt{a_t}}\exp\Big(\frac{b_t^2}{2a_t}\Big)\int_{\mathbb{R}} \frac{1}{\sqrt{2\pi}} \exp\Big(-\frac{(y-\frac{2b_t}{\sqrt{a_t}})^2}{2}\Big)dy \\
=&\frac{1}{\sqrt{a_t}}\exp\Big(\frac{b_t^2}{2a_t}\Big).
\end{aligned}$$

According to the assumptions $a_t = 1 - \epsilon\sigma_t^2$ is positive and the expectation is convergent for a small ϵ and its value is

$$\begin{aligned}
\mathbb{E}\Big[\exp\Big(\frac{\epsilon}{2}\lambda_t^2\Big)\Big] &= \frac{1}{\sqrt{a_t}}\exp\Big(\frac{\epsilon\mu_t^2}{2}\Big)\exp\Big(\frac{b_t^2}{2a_t}\Big) \\
&= \frac{1}{\sqrt{1-\epsilon\sigma_t^2}}\exp\Big(\frac{\epsilon\mu_t^2}{2}\Big)\exp\Big(\frac{\epsilon^2\mu_t^2\sigma_t^2}{2-2\epsilon\sigma_t^2}\Big).
\end{aligned}$$

Thus the integral in (4.14) is finite and the exponential term in (4.13) is integrable.

In order to show Z_t is a martingale we first consider that Z_t is a local martingale, hence it is a supermartingale. Therefore, Z_t is a martingale if and only if the condition $\mathbb{E}[Z_t] = 1$, $\forall t \in [0, T]$, is satisfied. This martingale property can be shown by induction. Suppose $\mathbb{E}[Z_0] = 1$ which is trivial and $\mathbb{E}[Z_t] = 1$ for $t \in [0, S]$ for $S < T$. Let now $t \in [S, S+\epsilon]$ and set

$$Z_S^t = \exp\Big(\int_S^t \lambda_s dW_s - \frac{1}{2}\int_S^t \lambda_s^2 ds\Big).$$

According to Novikov condition and (4.13), Z_S^t is a martingale. Then we have

$$\mathbb{E}[Z_t] = \mathbb{E}[Z_S Z_S^t] = \mathbb{E}[\mathbb{E}[Z_S Z_S^t]|\mathcal{F}_S] = \mathbb{E}[Z_S\mathbb{E}[Z_S^t|\mathcal{F}_S]] = \mathbb{E}[Z_S Z_S^S] = \mathbb{E}[Z_S],$$

since

$$Z_S^S = \exp\Big(\int_S^S \lambda_s dW_s - \frac{1}{2}\int_S^S \lambda_s^2 ds\Big) = \exp(0) = 1.$$

It follows

$$\mathbb{E}[Z_t] = \mathbb{E}[Z_S] = 1 \quad \text{for } t \in [S, S+\epsilon].$$

Then we have $\mathbb{E}[Z_t] = 1$ for $t \in [0, S + \epsilon]$. Repeat this induction for $\frac{T-S}{\epsilon}$ times we have $\mathbb{E}[Z_t] = 1$ for $t \in [0, T]$, which implies Z_t defined in (4.12) is a martingale.

□

To calibrate the model we use the transformed price process to avoid complex numerical calculations in the calibration procedure. The bivariate model can be reformulated as

$$d\xi_t = \left(\frac{1}{2} z_t \xi_t + \sqrt{z_t}\lambda_t\right) dt + \sqrt{z_t} dW_t^1, \tag{4.15}$$

$$d\lambda_t = \theta(\bar{\lambda} - \lambda_t)dt + \sigma_\lambda dW_t^2, \tag{4.16}$$

$$dW_t^1 dW_t^2 = \rho dt. \tag{4.17}$$

In SDE (4.16), $\bar{\lambda}$ represents the long-term mean value. θ denotes the rate with which the shocks dissipate and the variable reverts towards the mean. σ_λ is the volatility of the market price of risk. The price transformation has been proved to be conditional Gaussian and its SDE can be solved explicitly.

4.3.2 Calibration to historical data

We consider the discretization of the model (4.15)-(4.17). By assuming constant volatility terms in the time interval $[t_{k-1}, t_k]$, the model equations can be discretized under Euler's scheme given by

$$\xi_{t_k} = \sqrt{z_{t_{k-1}}} \triangle t \lambda_{t_{k-1}} + \left(1 + \frac{1}{2} z_{t_{k-1}}\right) \xi_{t_{k-1}} + \sqrt{z_{t_{k-1}} \triangle t} \mathcal{E}_{t_k}^1, \tag{4.18}$$

$$\lambda_{t_k} = (1 - \theta \triangle t)\lambda_{t_{k-1}} + \theta \bar{\lambda} \triangle t + \sigma_\lambda \sqrt{\triangle t} \mathcal{E}_{t_k}^2, \tag{4.19}$$

$$Cov(\mathcal{E}_{t_k}^1, \mathcal{E}_{t_k}^2) = \rho, \tag{4.20}$$

where $\triangle t = t_k - (t_{k-1})$, namely the time interval, and $\mathcal{E}_{t_k}^1$, $\mathcal{E}_{t_k}^2 \sim \mathcal{N}(0,1)$. z_{t_k} can be modeled by using the function $\beta(T - t_k)^{-\alpha}$. The model parameter-set is therefore $\psi = [\theta, \bar{\lambda}, \sigma_\lambda, \rho, \alpha, \beta]$.

As λ_{t_k} is a hidden state variable related to the price transformation, and only values of ξ_{t_k} at time points $t_1, t_2, ...t_n$ can be determined from the market observations, the market price of risk series can be estimated by applying the Kalman filter algorithm. We have chosen to use the transformation process instead of the normalized price a_{t_k}. Because of the linear form of Equations

(4.18) and (4.19) the standard Kalman filter algorithm is considered to be an efficient method for the model calibration. A detailed procedure to apply the standard Kalman filter can be found in (Harv 89). To apply the Kalman filter model Equations (4.18)-(4.20) must be put into the state space representation to fit the model framework. The measurement equation links the unobservable state to observations. It can be derived from (4.18) and (4.19). After some manipulations, the state space form of the model can be rewritten as

$$S_{t_k} = \sqrt{\beta(T-t_k)^{-\alpha}}\triangle t\lambda_{t_k} + \left(1+\frac{1}{2}(\beta(T-t_k)^{-\alpha})\right)\xi_{t_k} + \sqrt{\beta(T-t_k)^{-\alpha}\triangle t}\bar{\mathcal{E}}^1_{t_k}, \tag{4.21}$$

$$\begin{aligned}\lambda_{t_k} &= (1-\theta\triangle t-\sigma_\lambda\rho\triangle t)\lambda_{t_{k-1}} + \sigma_\lambda\sqrt{(1-\rho^2)\triangle t}\bar{\mathcal{E}}^2_{t_k} \\ &\quad + \left[\theta\bar{\lambda}\triangle t - \frac{\sigma_\lambda\rho}{\sqrt{\beta(T-t_k)^{-\alpha}}}\left(\left(1+\frac{1}{2}(\beta(T-t_k)^{-\alpha})\right)\xi_{t_{k-1}} - \xi_{t_k}\right)\right],\end{aligned} \tag{4.22}$$

where $\bar{\mathcal{E}}^1_{t_k}$ and $\bar{\mathcal{E}}^2_{t_k}$ are independent, standard normally distributed random variables.

To achieve this form consider the equations (4.18)-(4.20). We want to put the model into the state space form. Price transformation depends on the current level of the market price of risk, which is an unobservable variable and therefore must be modeled in the equation of λ_{t_k}. We first let

$$\mathcal{E}^1_{t_k} = \bar{\mathcal{E}}^1_{t_k}, \qquad \mathcal{E}^2_{t_k} = \sqrt{1-\rho^2}\bar{\mathcal{E}}^2_{t_k} + \rho\bar{\mathcal{E}}^1_{t_k},$$

where $\bar{\mathcal{E}}^1_{t_k}$ and $\bar{\mathcal{E}}^2_{t_k}$ are both random variables of the standard normal distribution as well. This fact can be easily seen since we have

$$\begin{aligned}Cov(\bar{\mathcal{E}}^1_{t_k}, \bar{\mathcal{E}}^2_{t_k}) &= Cov\left(\mathcal{E}^1_{t_k}, \frac{\mathcal{E}^2_{t_k} - \rho\mathcal{E}^1_{t_k}}{\sqrt{1-\rho^2}}\right) \\ &= Cov\left(\mathcal{E}^1_{t_k}, \frac{\mathcal{E}^2_{t-k}}{\sqrt{1-\rho^2}}\right) + Cov\left(\mathcal{E}^1_{t_k}, -\frac{\rho\mathcal{E}^1_{t_k}}{\sqrt{1-\rho^2}}\right) = 0.\end{aligned}$$

Note that

$$\sqrt{z_{t_{k-1}}}\triangle t\lambda_{t_{k-1}} + \left(1+\frac{1}{2}z_{t_{k-1}}\right)\xi_{t_{k-1}} + \sqrt{z_{t_{k-1}}\triangle t}\mathcal{E}^1_{t_k} - \xi_{t_k} = 0.$$

Multiplying $-\sigma_\lambda\rho(z_{t_{k-1}})^{-\frac{1}{2}}$ at the both sides of the equation and sum it to the equation of λ_{t_k}, it follows that

$$\begin{aligned}\lambda_{t_k} &= (1-\theta\triangle t)\lambda_{t_{k-1}} - \sigma_\lambda\rho\triangle t\lambda_{t_{k-1}} + \theta\bar{\lambda}\triangle t,\\ &\quad - \frac{\sigma_\lambda\rho}{\sqrt{z_{t_{k-1}}}}\left(\left(1+\frac{1}{2}z_{t_{k-1}}\right)\xi_{t_{k-1}} - \xi_{t_k}\right) + \sigma_\lambda\sqrt{\triangle t}\mathcal{E}^2_{t_k} - \sigma_\lambda\sqrt{\triangle t}\rho\mathcal{E}^1_{t_k}\\ &= (1-\theta\triangle t - \sigma_\lambda\rho\triangle t)\lambda_{t_{k-1}} + \left[\theta\bar{\lambda}\triangle t - \frac{\sigma_\lambda\rho}{\sqrt{z_{t_{k-1}}}}\left(\left(1+\frac{1}{2}z_{t_{k-1}}\right)\xi_{t_{k-1}} - \xi_{t_k}\right)\right]\\ &\quad + \sigma_\lambda\sqrt{\triangle t}\sqrt{1-\rho^2}\mathcal{E}^2_{t_k}.\end{aligned}$$

This is the transition equation in the state space form, and the measurement equation is given by

$$S_{t_k} = \xi_{t_{k+1}} = \sqrt{z_{t_k}}\triangle t\lambda_{t_k} + \left(1+\frac{1}{2}z_{t_k}\right)\xi_{t_k} + \sqrt{z_{t_k}\triangle t}\mathcal{E}^1_{t_k}.$$

For the estimation of the parameter vector $\psi = [\theta, \bar{\lambda}, \sigma_\lambda, \rho, \alpha, \beta]$ consider the variable ξ_{t_k}. In each iteration of the filtering procedure, the conditional mean $\mathbb{E}[\xi_{t_k}|\xi_{t_1}, ..., \xi_{t_{k-1}}]$ and the conditional variance $Var(\xi_{t_k}|\xi_{t_1}, ..., \xi_{t_{k-1}})$ can be calculated. We denote the mean and variance by $\mu_{t_k}(\psi)$ and $\Sigma_{t_k}(\psi)$, respectively. The joint probability density function of the observations is denoted by $f(\xi_{t_{1:n}}|\psi)$ and is given by

$$f(\xi_{t_{1:n}}|\psi) = \prod_{k=1}^{n}\frac{1}{\sqrt{2\pi\Sigma_{t_k}(\psi)}}\exp\left(-\frac{(\xi_{t_k}-\mu_{t_k}(\psi))^2}{2\Sigma_{t_k}(\psi)}\right),$$

where $\xi_{t_{1:n}}$ summarize the observations from ξ_{t_1} to ξ_{t_n}. Its corresponding log-likelihood function is given by

$$\mathcal{L}_{obs}(\psi|\xi_{t_{1:n}}) = -\frac{n}{2}\log 2\pi - \frac{1}{2}\sum_{k=1}^{n}\log\Sigma_{t_k}(\psi) - \frac{1}{2}\sum_{k=1}^{n}\frac{(\xi_{t_k}-\mu_{t_k}(\psi))^2}{\Sigma_{t_k}(\psi)}. \quad (4.23)$$

The estimation results, their standard errors, t-tests and p-values can be found in Table 4.3. Figure 4.7 shows the estimation results of the market price of risk, compared with the price transformation and the historical futures price. In Figure 4.8, a negative correlation between the price transformation and the market price of risk can be seen. The market price of risk is the return in excess of the risk-free rate that the market wants as compensation for taking the risk. It is a measure of the extra required rate of return, or say, a risk premium, that

Parameter	Coeff	Std Err	t-test	p-value
θ	1.5130	0.3195	5.7601	0.0000
$\bar{\lambda}$	0.4091	0.6117	4.0641	0.0001
σ_λ	0.2913	0.0193	17.6365	0.0000
ρ	0.0017	0.0016	9.0910	0.0000
α	-1.5772	0.0256	61.5603	0.0000
β	0.0172	0.0005	35.6312	0.0000

Table 4.3: Test of model parameters at significance level of 5%, sample size 1536

investors need for taking the risk. The more risky an investment is, the higher the additional expected rate of return should be. So in order to achieve a higher required rate of return, the asset must be discounted and thus will be sold at a lower price. For more economical explanations of the market price of risk see e.g. (Hull 09) and (Wilm 06) [1]. Figure 4.8 reveals this inverse relationship.

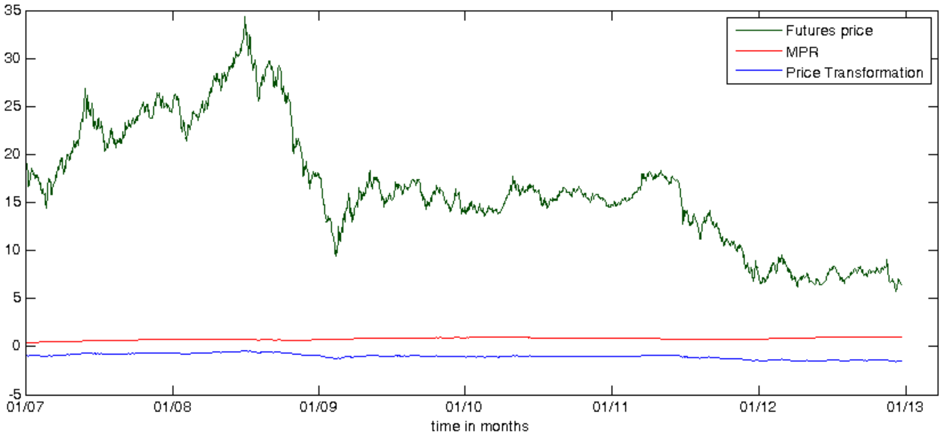


Figure 4.7: MPR, futures price and price transformation from 01.2007 to 12.2012.

Moreover, we use the mean pricing errors (MPE) and the root mean squared

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[1] See (Hull 09), Ch. 27. or (Wilm 06), Ch. 30.

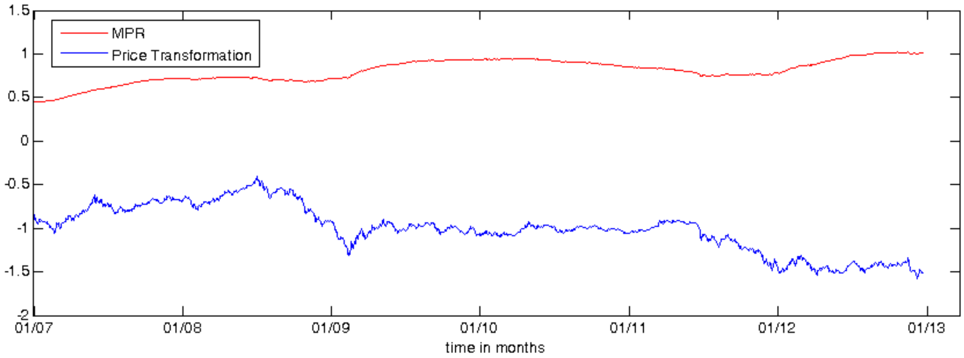

Figure 4.8: Negative correlation of MPR and price transformation.

Maturity	MPE	RMSE
1 month	-0.0153	0.0182
3 months	-0.0208	0.0234
6 months	-0.0366	0.0397
9 months	-0.1273	0.1302

Table 4.4: Performance of MPE and RMSE with 2000 observations

errors (RMSE) given by

$$MPE = \frac{1}{N}\sum_{t_i=1}^{N}(\bar{\xi}_{t_i,\tau} - \xi_{t_i,\tau}),$$

$$RMSE = \left(\frac{1}{N}\sum_{t_i=1}^{N}(\bar{\xi}_{t_i,\tau} - \xi_{t_i,\tau})^2\right)^{\frac{1}{2}},$$

respectively, to assess the quality of model fit. Here N denotes the number of observations, $\bar{\xi}_{t_i,\tau}$ is the estimated price to maturity τ, and $\xi_{t_i,\tau}$ is the observed price. Their values can be seen in Table 4.4. The absolute values of MPE and RMSE increase with time but still remain very low even 9 months before the maturity. Therefore, the conclusion is that the model is able to reproduce the price dynamics.

Figure 4.9 shows the standard statistical test results of the residuals by taking into account the dynamic market price of risk. Comparing with the results from Figure 4.2 to Figure 4.6, the time series of the residuals is relative stable with smaller variance. The sample auto-correlations and sample partial auto-correlations reveal very weak linear dependence of the variables at different time points. Also, the Q-Q plot indicates a better fit of a Gaussian distribution.

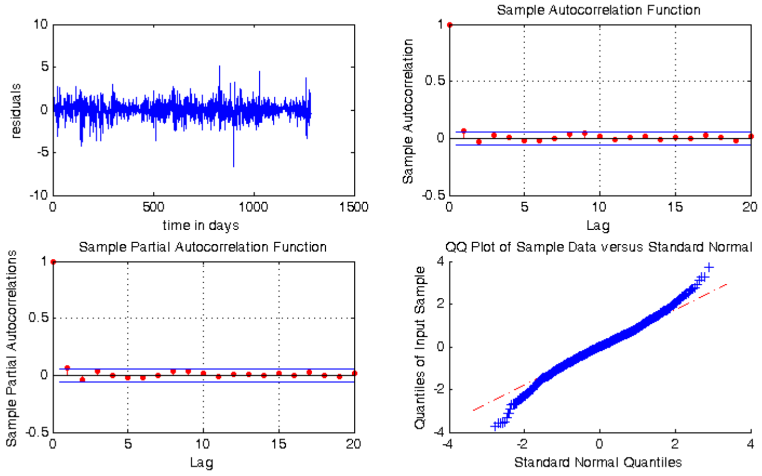

Figure 4.9: Statistical tests for the residuals.

4.4 Option Pricing and Market Forward Looking Information

A general pricing formula of a European call is given by

$$C_t = e^{-\int_t^\tau r_s ds}\mathbb{E}^{\mathbb{Q}}[(A_\tau - K)^+ | \mathcal{F}_t],$$

where $\{r_s\}_{s\in[0,T]}$ stands for a deterministic rate, A_t denotes the futures price, $K \geq 0$ is the strike price, and $\tau \in [0, T]$ is the maturity. The normalized price process a_t is given by $a_t = A_t/p$, where P denotes the penalty for each ton of exceeding emissions, and therefore we have $A_t = p\Phi(\xi_t)$. A call option price formula written on EUA has been derived by Carmona and Hinz in (CarH 11) under the assumption of a constant market price of risk. Under the assumption of a dynamic market price of risk, the option price formula is coherent with the formula of Carmona and Hinz given by

$$C_t = e^{-\int_t^\tau r_s ds}\int_{\mathbb{R}} (p\Phi(x) - K)^+ \varphi(\mu_{t,\tau}, \sigma_{t,\tau}^2) dx,$$

where φ stands for the density function of a standard normal distribution. Here $\mu_{t,\tau}$ and $\sigma_{t,\tau}^2$ are the parameters of the distribution of ξ_t, which is conditional Gaussian. Under the risk neutral measure $\mathbb{Q}$, $\mu_{t,\tau}$ and $\sigma_{t,\tau}^2$ are given by

$$\mu_{t,T} = e^{\frac{1}{2}\int_t^T z_s ds}\xi_t, \qquad \sigma^2_{t,T} = \int_t^T z_s e^{\int_s^T z_u du} ds.$$

In the following example, the penalty level is $p = 100$, the initial time $t = 0$ starts in April 2005. EUA futures has maturity T on the last trading day in 2012. The European calls written on EUA futures with a strike at $K = 15$ and maturity T will be considered under a constant interest rate at $r = 0.05$. Figure 4.10 shows the call option prices and the futures prices. The red curve stands for the option prices under dynamic MPR while the green curve stands for the option prices under constant MPR.

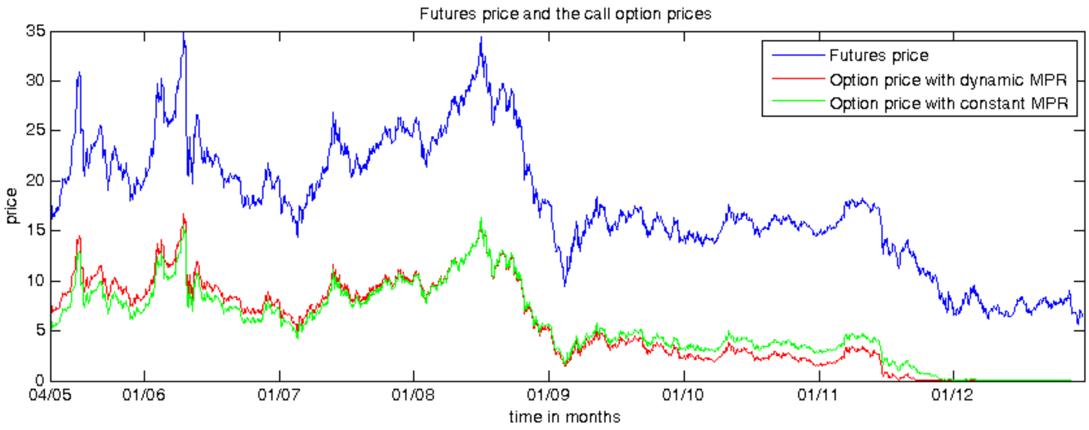

Figure 4.10: Futures price and call option prices with $K = 15$ from 2005 to 2012.

To measure the impact of the dynamic market price of risk on the EUA option for different strikes we calculate the option price in the univariate and bivariate model setting respectively. Durations from 1, 3, 6 and 12 months to maturity are chosen for calls written on EUA 2012. The results are plotted in Figure 4.11. The red curve stands for the option prices evaluated by the bivariate model and the green curve by the univariate model. The blue line is the corresponding futures price at the given time. In most cases, one is interested in the option prices by which their corresponding strike prices are near the underlying prices. According to the figure, the option prices in different model settings coincide except for a interval around the corresponding futures. In a short time before the maturity of EUA 2012, Figure 4.11 shows a price overestimation by the constant MPR. This result is consistent with the result shown in Figure 4.10, where we take the strike $K = 15$ as a sample path.

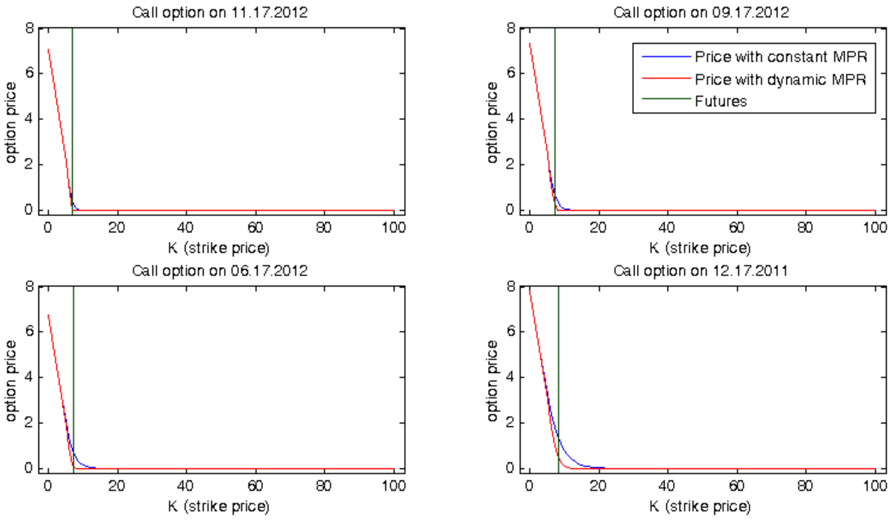

Figure 4.11: Call option prices comparison for durations of 1, 3, 6, 12 months on EUA 2012 for different strikes.

Moreover, one notes that the call price process with constant MPR develops below the call process with dynamic MPR in the first trading phase before 2008 and then increases slowly and moves to the upside of the call process with dynamic MPR during the second trading phase, before both processes vanish to the maturity because of lower underlying prices. The reason for the price underestimation before 2008 and overestimation thereafter can be explained as the assumption of a constant MPR in the whole trading periods and thus causes a neglect on the information of the market participants. Due to the regulatory framework of the carbon market, certificates carry information on the market participants expectations on the development of the fundamental price drivers. Since the implied risk premia increase with time and exceed their ‘average’ level in 2008, asset price must be discounted to compensate the higher risk. By using appropriate valuation models, this risk premia and the forward-looking information carried by prices of futures and options of certificates can be extracted.

4.5 Further Discussion on Modelling EUA Prices

4.5.1 Introduction of pricing theory

For modelling the EUA prices, Carmona et al. in (CFHP 10) has developed a stochastic equilibrium model of allowance price by assuming n individual companies. All companies behave in a way that their expected terminal wealth, by buying or selling an optimal number of allowance permits and producing an optimal quantity of goods, can be maximized. Meanwhile, a fictitious central planner can also minimize its expected total costs by producing an optimal quantity of goods. The optimization problems of Carmona et al. in (CFHP 10) are formulated in the way that profits and costs are expressed in time-T currency, which has the advantage that no discount factors could appear in the formulae of the optimization problems. The paper first proved that such a optimal solution exist, then it also derived a formula of time-t futures price of emission allowances given by

$$F_{t,T} = P \cdot \mathbb{E}[1_{\text{Non-Compliance Event}}|\mathcal{F}_t], \tag{4.24}$$

where P denotes the penalty fee that has to be paid for each tonne of emission not covered by a emission allowance at the compliance time T. The stochastic equilibrium model of Carmona et al. is of special interest because [1]:

- The model captures the main characteristics of an ordinary scheme;
- It is possible to derive the permit price formula analytically; and
- It is also the basis for the reduced-form model that can be used for parameter estimation in practice.

Generally, the non-compliance event can be expressed by the aggregated cumulative emission process, denoted by $q_{[0,T]}$. The non-compliance event is then given by $\{q_{[0,T]} > N\}$, where N is the total amount of allowance permits allocated by the policy regulator to the relevant companies, i.e. the cap. Therefore, (4.24) can be expressed as

$$F_{t,T} = P \cdot \mathbb{P}[q_{[0,T]} > N|\mathcal{F}_t]. \tag{4.25}$$

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[1] See explanation of Grüll in (Grue 10).

Intuitively, the time-t futures price of EUA allowance is given by the penalty multiplied by the probability of a permit shortage at the end of the compliance period.

The model of Chesney and Taschini in (CheT 12) specifies the process for the cumulative emissions in the frame work of Carmona et al. in (CFHP 10). Even though the model of Chesney and Taschini is developed independently from the model in the paper of Carmona et al., it can be categorized as a model in the general framework of it. In the paper of Chesney and Taschini, the emission process is described by an emission rate Q_t, which follows a geometric Brownian motion given by

$$Q_t = Q_0 \exp\left\{ \left(\mu - \frac{\sigma^2}{2} \right) t + \sigma W_t \right\},$$

where μ and σ are the two parameters of the geometric Brownian motion and W_t denotes the standard Brownian motion. Therefore, the cumulative emissions in the time period $[0,t]$ are given by

$$q_{[0,t]} = \int_0^t Q_s ds.$$

This means that the cumulative emissions are expressed by the integral over a geometric Brownian motion for which no closed-form density is available. The model of Chesney and Taschini approximates the cumulative emissions in the time interval $[t_1, t_2] \subseteq [0, T]$ by a linear approximation given by

$$q_{[t_1,t_2]} \approx Q_{t_2}(t_2 - t_1).$$

Furthermore, assuming that interest rate r is deterministic and there is no convenience yield as shown by Uhrig-Homburg and Wagner in (UhrW 09), the theoretical permit price from (4.25) is given by

$$S_t = P\, e^{-r(T-t)} \cdot \mathbb{P}[q_{[0,T]} > N | \mathcal{F}_t].$$

By applying the linear approximation, it can be proved that the permit price S_t at $0 \leq t \leq T$ has the following formula:

$$S_t = \begin{cases} P\, e^{-r(T-t)} & \text{if} \quad q_{[0,t] \geq N} \\ P\, e^{-r(T-t)} \cdot \Phi\left(\frac{-\ln\left(\frac{1}{T-t} \left[\frac{N - q_{[0,t]}}{Q_t} \right] \right) + \left(\mu - \frac{\sigma^2}{2} \right)(T-t)}{\sigma\sqrt{T-t}} \right) & \text{if} \quad q_{[0,t] < N} \end{cases} .$$

Moreover, the model of Grüll and Kiesel in (GruK 10) extended the model of Chesney and Taschini by using another two approximation approaches for the cumulative emissions:

- The log-normal (moment matching)

$$q_{[t_1,t_2]} \approx \log N(\mu_L(t_1,t_2), \sigma_L^2(t_1,t_2));$$

- The reciprocal gamma (moment matching)

$$q_{[t_1,t_2]} \approx IG(\alpha_{IG}, \beta_{IG}),$$

where the parameters $\mu_L(t_1,t_2)$ and $\sigma_L^2(t_1,t_2)$ and α_{IG} and β_{IG} are chosen such that the first two moments of $\log N(\mu_L(t_1,t_2), \sigma_L^2(t_1,t_2))$ and $IG(\alpha_{IG}, \beta_{IG})$, respectively, match those of $q_{[t_1,t_2]}$. Then according to (Grue 10), the derivation of the allowance permit price for these two different approximation approaches is split up into the following three steps:

1. Compute the first two moments of $q_{[t_1,t_2]} = \int_{t_1}^{t_2} Q_s ds$.
2. Derive the parameters of the random variables that are used to approximate the cumulative emissions.
3. Derive the permit price formula for the two different moment matching approaches.

4.5.2 Choosing appropriate cumulative emission process

In stead of modelling the emission rate, it is also possible to model the emission process directly. Follow the idea that the allowance price is calculated by multiplying the penalty and the probability of a permit shortage at the end of the compliance period, consider the aggregated cumulative emission process as a subordinator $G_{t,T}$ for $0 \leq t \leq T$. If other notations remain the same, then time-t futures price of allowance permit is given by

$$F_{t,T} = P \cdot \mathbb{P}[G_{0,T} > N|\mathcal{F}_t],$$

where the subordinator $G_{t,T}$ of aggregated cumulative emission process starts at the beginning of the compliance period. Then from the natural characteristics of a subordinator it is easy to see that

$$\begin{aligned} S_t &= P\,e^{-r(T-t)} \cdot \mathbb{P}[G_{0,T} > N|\mathcal{F}_t] \\ &= P\,e^{-r(T-t)} \cdot \mathbb{P}[G_{0,t} + G_{t,T} > N|\mathcal{F}_t] \\ &= P\,e^{-r(T-t)} \cdot \mathbb{P}[G_{t,T} > N - G_{0,t}] \\ &= P\,e^{-r\tau} \cdot \mathbb{P}[G_\tau > N - G_{0,t}], \end{aligned} \tag{4.26}$$

where $\tau = T - t$ denotes the rest of lifetime to the compliance deadline.

Consider the case that the cumulative emission process follows the inverse Gaussian subordinator IG_t. The inverse Gaussian subordinator is defined as a stochastic process with

- $(IG_t - IG_s)$ and $(IG_k - IG_l)$ are stochastic independent $\forall t > s \geq k > l \geq 0$.
- $(IG_t - IG_s)$ is inverse Gaussian distributed, i.e. $(IG_t - IG_s) \sim IG(g(t) - g(s), \eta(g(t) - g(s))^2)$, $\forall t > s \geq 0$ and $g(t)$ is a monotone increasing function with $g(t) > 0, \forall t > 0$.

Let $g(0) = 0$ and $IG_0 = 0$, then we have $IG_t \sim IG(g(t), \eta g(t)^2)$ with mean $g(t)$ and variance $g(t)/\eta$. The density function of an inverse Gaussian distribution IG_t is given by

$$f_X(x; g(t), \eta g(t)^2) = \frac{\sqrt{\eta} g(t)}{\sqrt{2\pi} x^{\frac{3}{2}}} \exp\left(-\frac{\eta g(t)^2 (x - g(t))^2}{2 g(t)^2 x}\right). \tag{4.27}$$

And we can derive the cumulative distribution function of an inverse Gaussian distributed random variable.

Proposition 4.5.1. *If the density of a random variable is given by (4.27), then its cumulative distribution function is given by*

$$F_X(x; g(t), \eta g(t)^2) = \Phi\left(\sqrt{\frac{\eta}{x}}(x - g(t))\right) + \exp(2\eta g(t))\Phi\left(-\sqrt{\frac{\eta}{x}}(x + g(t))\right), \tag{4.28}$$

where $\Phi(\cdot)$ denotes the cumulative distribution function of standard normal.

Proof. Only the proof idea will be given here. Let $\varphi(\cdot)$ be the density function of a standard normal distributed random variable. If the cumulative distribution function of an inverse Gaussian distributed random variable is given by (4.28), then we have

$$\begin{aligned}\frac{\partial F_X}{\partial x} =&\varphi\left(\sqrt{\frac{\eta}{x}}(x-g(t))\right)\left(\sqrt{\frac{\eta}{x}}(x-g(t))\right)' \\ &+\exp(2\eta\, g(t))\,\varphi\left(-\sqrt{\frac{\eta}{x}}(x+g(t))\right)\left(-\sqrt{\frac{\eta}{x}}(x+g(t))\right)' \\ =&\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{\eta}{2x}\,(x-g(t))^2\right)\left(\frac{1}{2}\sqrt{\eta}x^{-\frac{1}{2}}+\frac{1}{2}\sqrt{\eta}\,g(t)\,x^{-\frac{3}{2}}\right) \\ &+\frac{1}{\sqrt{2\pi}}\exp(2\eta g(t))\exp\left(-\frac{\eta}{2x}\,(x+g(t))^2\right)\left(-\frac{1}{2}\sqrt{\eta}x^{-\frac{1}{2}}+\frac{1}{2}\sqrt{\eta}\,g(t)\,x^{-\frac{3}{2}}\right) \\ =&\frac{\sqrt{\eta}\,g(t)\,x^{-\frac{3}{2}}}{\sqrt{2\pi}}\exp\left(-\frac{\eta}{2x}(x-g(t))^2\right) \\ =&\frac{\sqrt{\eta}g(t)}{\sqrt{2\pi}x^{\frac{3}{2}}}\exp\left(-\frac{\eta g(t)^2(x-g(t))^2}{2g(t)^2x}\right).\end{aligned}$$

□

Now consider the probability $\mathbb{P}[IG_t > \widetilde{N}]$ for some $\widetilde{N} \in \mathbb{R}$, then from Proposition 4.5.1 it is not difficult to see that

$$\begin{aligned}\mathbb{P}[IG_t > \widetilde{N}] &= 1-\mathbb{P}[IG_t \le \widetilde{N}] = 1-F_X(\widetilde{N}) \\ &= \Phi\left(\sqrt{\frac{\eta}{\widetilde{N}}}(g(t)-\widetilde{N})\right)-\exp\left(2\eta g(t)\right)\Phi\left(-\sqrt{\frac{\eta}{\widetilde{N}}}(g(t)+\widetilde{N})\right).\end{aligned}$$

According to the limit behavior of IG_t, if t is large, e.g. one considers t as the days to maturity, then $\eta g(t)$ is large and IG_t is approximately normal distributed with mean $g(t)$ and variance $g(t)/\eta$. This yields

$$\begin{aligned}\mathbb{P}[IG_t > \widetilde{N}] = 1-\mathbb{P}[IG_t \le \widetilde{N}] &\approx 1-\Phi\left(\frac{\widetilde{N}-g(t)}{\sqrt{\frac{g(t)}{\eta}}}\right) \\ &= \Phi\left(\frac{\sqrt{\eta}g(t)-\sqrt{\eta}\widetilde{N}}{\sqrt{g(t)}}\right) = \Phi\left(\sqrt{\eta g(t)}-\frac{\sqrt{\eta}\widetilde{N}}{\sqrt{g(t)}}\right). \qquad (4.29)\end{aligned}$$

In particular, if we assume $g(t) = \nu t, \nu > 0$, then (4.29) becomes

$$\mathbb{P}[IG_t > \widetilde{N}] = \Phi\left(\sqrt{\eta\nu t}-\frac{\sqrt{\eta}\widetilde{N}}{\sqrt{\nu t}}\right). \qquad (4.30)$$

The event $\{IG_t > \widetilde{N}\}$ means the cumulative emissions will excess the threshold level $\widetilde{N}$ at time t. If we denote $T_{\widetilde{N}}$ by the time the cumulative emissions is more than $\widetilde{N}$, then we have

$$\mathbb{P}[T_{\widetilde{N}} < t] = \mathbb{P}[IG_t > \widetilde{N}] = \Phi\left(\sqrt{\eta\nu t} - \frac{\sqrt{\eta}\widetilde{N}}{\sqrt{\nu t}}\right).$$

Therefore, by using the approximate results, the allowance permit price in (4.26) can be expressed by the following formula:

$$S_t = P\, e^{-r\tau} \cdot \Phi\left(\sqrt{\eta\nu\tau} - \frac{\sqrt{\eta}(N - G_{0,t})}{\sqrt{\nu\tau}}\right). \tag{4.31}$$

Formula (4.31) provides an alternative way to model the allowance price approximately. Unlike the model in (CheT 12) and (GruK 10), it does not model the emission rate and use the integral to calculate the cumulative emissions, but model the aggregated cumulative emission process directly. And then use the limit behavior of the Inverse Gaussian process to reformulate the shortage probability so that a relative simpler price formula can be derived.

Furthermore, consider (4.29) in the following way:

$$\begin{aligned}\mathbb{P}[IG_t > \widetilde{N}] &= \Phi\left(\sqrt{\eta\nu t} - \frac{\sqrt{\eta}\widetilde{N}}{\sqrt{\nu t}}\right)\\ &= \Phi\left(\sqrt{\eta\widetilde{N}}\left[\left(\frac{t}{\widetilde{N}/\nu}\right)^{\frac{1}{2}} - \left(\frac{\widetilde{N}/\nu}{t}\right)^{\frac{1}{2}}\right]\right)\\ &= \Phi\left(\frac{1}{\alpha}\left[\left(\frac{t}{\beta}\right)^{\frac{1}{2}} - \left(\frac{\beta}{t}\right)^{\frac{1}{2}}\right]\right),\end{aligned}$$

with $\alpha = \sqrt{\eta\widetilde{N}}^{-1}$ and $\beta = \widetilde{N}/\nu$. One notes immediately that this is the cumulative distribution function of a Birnbaum-Saunders distribution with α being the shape parameter and β being the scale parameter. The Birnbaum-Saunders distributed random variable has positive value and its density is given by

$$f_{T_N}(t;\alpha,\beta) = \frac{1}{2\sqrt{2\pi}\alpha\beta}\left(\left(\frac{\beta}{t}\right)^{\frac{1}{2}} + \left(\frac{\beta}{t}\right)^{\frac{3}{2}}\right) \cdot \exp\left[-\frac{1}{2\alpha^2}\left(\frac{t}{\beta} + \frac{\beta}{t} - 2\right)\right].$$

with α, $\beta > 0$ and $0 < t < \infty$. Therefore, we conclude that the random variable $T_{\widetilde{N}}$ is approximately Birnbaum-Saunders distributed. And the EUA futures price has the formula

$$F_{t,T} = P \cdot \Phi \left(\frac{1}{\alpha} \left[\left(\frac{\tau}{\beta} \right)^{\frac{1}{2}} - \left(\frac{\beta}{\tau} \right)^{\frac{1}{2}} \right] \right),$$

with parameters $\alpha = \sqrt{\eta(N - G_{0,t})}^{-1}$ and $\beta = (N - G_{0,t})/\nu$. The EUA allowance price is then given by

$$S_t = P\, e^{-r\tau} \cdot \Phi \left(\frac{1}{\alpha} \left[\left(\frac{\tau}{\beta} \right)^{\frac{1}{2}} - \left(\frac{\beta}{\tau} \right)^{\frac{1}{2}} \right] \right).$$

5

Linking Systems and Effect of Carbon Prices

5.1 Introduction

The issue to link emission trading schemes has been discussed and studied by politicians, market regulators and scientists for several years. Linking means to combine different emission trading schemes together so that emission certificates can be used in both of them for their compliance purposes. Nowadays there are a number of emission trading schemes in many countries. Some of them are advancing linking of their emission trading schemes, e.g. California and Quebec. Some of them are discussing the proposal of doing it, e.g. EU ETS and Swiss ETS; China ETS and Korea ETS. From the economic point of view, linking different schemes would create larger market and help to obtain significant benefit. First of all, linking means to strengthen international carbon markets, which would unlock further efficiencies and contribute to reducing emission pollution cost-effectively. It provides the opportunity to achieve the emission reduction goals by shifting reductions between both of the linked systems so that the total reduction costs can be minimized. Second, linking enlarge the market for CO2 certificates so that the market liquidity can be improved. A liquid market helps to reduce the carbon price volatility and ensure the market stability. Moreover, to a certain extent linking systems can compensate for regulatory defects of the carbon market and helps to achieve a collective emission target in a cost-efficient way. A over-allocated market may cause the price collapse in a single trading system, but linking would reduce this risk. When link two schemes with different prices, the price behavior of emission permits should plays the central role for the trading market. However, whether and how prices vary depends on the way the systems are linked. Our research focuses on this problem and tries to address the issue of the carbon price behavior as well as the market balance of linking systems mathematically and economically.

In theory, companies with relative low abatement costs will choose to emit less and sell surplus emission allowances on the carbon market, whereas companies with high abatement costs will choose to purchase allowances to cover their emissions. Therefore, emissions reductions are undertaken in the most cost-efficient way. Meanwhile, low cost abatement opportunities are geographically spread over the globe, so that linking would help to deplete these opportunities as far as possible and ensure the full cost-efficiency. For its theoretical explanation see for example Edenhofer et al. in (EdFM 07), Anger et al. in (AnBO 09), Mehling and Haites in (MehH 09) and Haites and Mehling in (HaiM 09). Linking system for emission trading schemes has been discussed by some literature from an economical point of view. Grüll and Taschini in (GruT 12) use a simple model-free structure discuss the price behavior of linking systems under different model settings. For the research of linking under equilibrium framework, Barrieu and Fehr in (BarF 11) focus on arbitrage free price dynamics for CERs and EUAs of the second compliance periods. They discuss the impact of the regulation on the different emission certificates using an equilibrium model and analyze the simulation methods of futures price processes. Similar research on relationship between EUAs and CERs can be seen in Nazifi in (Nazi 10). Besides, some empirical studies on linking schemes can be found in (JotB 09) and (RanS 15).

This chapter is organized as follows. Based on the qualitative analysis of Grüll and Taschini in (GruT 12), we develop a market equilibrium model of linking system on deterministic settings and investigate the price convergence behavior of the model. In section 2, a model based on bilateral linking mechanism will be established and analyzed. Then in section 3, a model of unilateral setting will be developed and key results will be provided. Results of market equilibrium position and price convergence behavior coincide with results in (GruT 12), which corroborate their opinions from a quantitative standpoint.

In section 4 we introduce the status of international linking systems and discuss their potential impacts.

5.2 Model of Bilateral Systems

We consider two emission trading schemes, both of them are using cap-and-trade systems and are constructing a link depending on the regulation of allowable permit transfer. The first option is to use the bilateral linking system. A bilateral system allows permits to be traded in both schemes which means the transfer of allowance permits is bidirectional. If two trading schemes with different allowance prices are linked, a price convergence may take place. In order to demonstrate this problem, an equilibrium model will be developed in the following subsection.

5.2.1 Model description

Suppose two emission trading schemes ETS1 and ETS2 are to be linked under the bilateral mechanism, where allowance permits can be transferred in both directions. Following assumptions are made:

- The permit price processes in ETS1 and ETS2 are denoted by $(A_t)_{t\in[0,T]}$ and $(B_t)_{t\in[0,T]}$ over a certain compliance period. A and B are the futures prices with maturity at T, respectively.
- There is a finite set of agents, I, covered by the ETS1, which is different from a finite set of agents, J, covered by ETS2.
- Each agent $i \in I$, $j \in J$ will have some emissions E^i and Z^j in the corresponding compliance period, respectively.
- Each agent $i \in I$, $j \in J$ will be allocated by a certain number of allowances, denoted by Λ^i and Ψ^j at the beginning of the period, respectively.
- Agent i can adjust its position by buying or selling $\phi^i \in \mathbb{R}$ allowances in ETS1 at price A. Similarly, j can buy or sell $\theta^j \in \mathbb{R}$ allowances in ETS2 at price B.

- γ^i and δ^j denote the amount of allowance permits, which i and j can buy from or sell to the other market, respectively.

Furthermore, under the model assumptions, we set constraints for γ^i and δ^j given by

$$\widetilde{\Gamma}^i \leq \gamma^i \leq \Gamma^i, \qquad \widetilde{\Delta}^j \leq \delta^j \leq \Delta^j.$$

The net amount for i and j at the end of the period are given by

$$\alpha^i = \Lambda^i + \phi^i + \gamma^i - E^i \qquad \text{and} \qquad \beta^j = \Psi^j + \theta^j + \delta^j - Z^j,$$

respectively. Moreover, we assume that each agent associates the net amount α^i and β^j with a projected Profit-and-Loss function, denoted by $\mathscr{A}^i(\alpha^i)$ and $\mathscr{B}^j(\beta^j)$. Therefore, each agent i has a cost function given by

$$\mathscr{L}^{A,B,i}(\phi^i, \gamma^i) = \phi^i A + \gamma^i(A, B) - \mathscr{A}^i(\alpha^i) \quad \forall i \in I,$$

while each agent j has a cost function given by

$$\mathscr{M}^{A,B,j}(\theta^j, \delta^j) = \theta^j B + \delta^j(A, B) - \mathscr{B}^j(\beta^j) \quad \forall j \in J.$$

For our equilibrium modelling, some standard assumptions have to be made as well:

Assumption 5.2.1. *(i) $\alpha^i \mapsto \mathscr{A}^i(\alpha^i)$ and $\beta^j \mapsto \mathscr{B}^j(\beta^j)$ are strong monotonically increasing, concave and continuously differentiable for $i \in I$ and $j \in J$.*
(ii) $\Gamma^i > 0, \widetilde{\Gamma}^i < 0$ for all $i \in I$. $\Delta^j > 0, \widetilde{\Delta}^j < 0$ for all $j \in J$.

In the following, $S^i = \mathbb{R} \times [\widetilde{\Gamma}^i, \Gamma^i]$ denotes the feasible compliance strategy of any agent i, and $S^j = \mathbb{R} \times [\widetilde{\Delta}^j, \Delta^j]$ denotes the feasible compliance strategy of any agent j. Therefore, $S = \{(\phi, \gamma, \theta, \delta) | (\phi^i, \gamma^i) \in S^i, (\theta^j, \delta^j) \in S^j, \forall i \in I, j \in J\}$ is the feasible compliance strategy for the overall market. Following the intuition that every agent aims to minimize its own cost, we can define the market equilibrium:

Definition 5.2.1. *Prices $(A^*, B^*) \in \mathbb{R}^2$ and the compliance strategy for the overall market $(\phi^*, \gamma^*, \theta^*, \delta^*) \in S$ form a market equilibrium, if the following conditions are satisfied:*
(i) All financial positions within each trading scheme are in zero net supply, i.e.

$$\sum_{i \in I} \phi^{*i} = 0, \qquad \sum_{j \in J} \theta^{*j} = 0.$$

(ii) All financial positions between trading schemes are in zero net supply, i.e.

$$\sum_{i\in I}\gamma^{*i}+\sum_{j\in J}\delta^{*j}=0.$$

(iii) Agents $i\in I$ and $j\in J$ are satisfied with their own compliance strategies, namely:

$$\mathscr{L}^{A^*,B^*,i}(\phi^{*i},\gamma^{*i})\le\mathscr{L}^{A^*,B^*,i}(\phi^{i},\gamma^{i}),\qquad\forall(\phi^i,\gamma^i)\in S^i,$$
$$\mathscr{M}^{A^*,B^*,j}(\theta^{*j},\delta^{*j})\le\mathscr{M}^{A^*,B^*,j}(\theta^{j},\delta^{j}),\qquad\forall(\theta^j,\delta^j)\in S^j.$$

Moreover, to understand the price behavior and the market balance, we introduce the following aggregated notations, variables and P&L functions given by:

$$\gamma=\sum_i\gamma^i,\qquad\delta=\sum_j\delta^j,\qquad E=\sum_i E^i,\qquad Z=\sum_j Z^j,$$
$$\Lambda=\sum_i\Lambda^i,\qquad\Psi=\sum_j\Psi^j,\qquad\Gamma=\sum_i\Gamma^i,\qquad\Delta=\sum_j\Delta^j,$$
$$\alpha=\sum_i\alpha^i=\Lambda+\gamma-E,\qquad\beta=\sum_j\beta^j=\Psi+\delta-Z,$$
$$\mathscr{A}(\alpha)=\sup\left(\sum_i\mathscr{A}^i(\alpha^i)\right),\qquad\mathscr{B}(\beta)=\sup\left(\sum_j\mathscr{B}^j(\beta^j)\right).$$

So far, the model equilibrium setting is described and some important results, such as equilibrium prices and the market position will be derived in the subsequent subsection.

5.2.2 Model results

Suppose there is a representative planer who is responsible for regulating the linking markets. The optimization problem for a representative planer can be expressed as

$$\inf\quad\left(\sum_{i\in I}\mathscr{L}^{A,B,i}(\phi^i,\gamma^i)+\sum_{j\in J}\mathscr{M}^{A,B,j}(\theta^j,\delta^j)\right)\tag{5.1}$$

with constraints $\widetilde{\Gamma}\le\gamma\le\Gamma,\widetilde{\Delta}\le\delta\le\Delta$ and $-\gamma=\delta$. Note that this optimization problem can be reformulated as:

$$\begin{aligned}&\inf\nolimits_\gamma\quad(-\mathscr{A}(\Lambda+\gamma-E)-\mathscr{B}(\Psi-\gamma-Z))\\ &s.t.\quad\widetilde{\Gamma}-\gamma\le 0,\quad\gamma-\Gamma\le 0,\quad\widetilde{\Delta}+\gamma\le 0,\quad-\gamma-\Delta\le 0.\end{aligned}\tag{5.2}$$

Due to assumptions described in the previous subsection, (5.2) with its constraints is a convex optimization problem. Therefore, its optimal solution $\bar{\gamma}$ is given as a solution to the Karush-Kuhn-Tucker (KKT) conditions. Moreover, if we assume that ETS1 and ETS2 can trade their allowance permits freely amongst each other and consider the aggregated planer problem given as follows:

$$\begin{aligned} &\inf \left(\sum_{i\in I} \mathscr{L} + \sum_{j\in J} \mathscr{M} \right) \\ = &\inf \left(\sum_{i\in I} -\mathscr{A}^i(\Lambda^i - E^i + \phi^i + \gamma^i) + \sum_{j\in J} -\mathscr{B}^j(\Psi^j - Z^j + \theta^j + \delta^j) \right) \quad (5.3)\\ &s.t. \quad \widetilde{\Gamma}^i \le \gamma^i \le \Gamma^i, \quad \widetilde{\Delta}^j \le \delta^j \le \Delta^j, \quad \forall i \in I, j \in J, \\ &\sum_i \phi^i = 0, \quad \sum_j \theta^j = 0, \quad \sum_i \gamma^i + \sum_j \delta^j = 0. \end{aligned}$$

Then the market equilibrium can be proved and its equilibrium price can be derived in the following proposition.

Proposition 5.2.1. *If the above assumption holds true and $\bar{\gamma}$ is an optimal solution for the representative problem, then we have the following results:*
(i) The market equilibrium exits.
(ii) The equilibrium allowance prices in ETS1 and ETS2 are given by

$$A = \mathscr{A}'(\Lambda - E + \bar{\gamma}), \quad B = \mathscr{B}'(\Psi - Z - \bar{\gamma}),$$

respectively.

Proof. First, we solve the optimization problem of (5.2) with Karush-Kuhn-Tucker conditions. The KKT conditions are given as follows:

(i) Stationary condition:

$$-\mathscr{A}'(\Lambda + \gamma - E) + \mathscr{B}'(\Psi - \gamma - Z) - \mu_1 + \mu_2 + \mu_3 - \mu_4 = 0.$$

(ii) Complementary slackness condition:

$$\mu_1(\widetilde{\Gamma} - \gamma) = 0, \quad \mu_2(\gamma - \Gamma) = 0, \quad \mu_3(\widetilde{\Delta} + \gamma) = 0, \quad \mu_4(-\gamma - \Delta) = 0.$$

(iii) Primal feasibility:

$$\widetilde{\Gamma} - \gamma \le 0, \quad \gamma - \Gamma \le 0, \quad \widetilde{\Delta} + \gamma \le 0, \quad -\gamma - \Delta \le 0.$$

(iv) Dual feasibility:

$$\mu_1 \geq 0, \quad \mu_2 \geq 0, \quad \mu_3 \geq 0, \quad \mu_4 \geq 0.$$

We denote $o^* \in \mathbb{R}$ as the point which fulfills the condition

$$\mathscr{A}'(\Lambda + o^* - E) = \mathscr{B}'(\Psi - o^* - Z),$$

and discuss the following different cases of the primal feasibility:

In case of $\gamma = max(\widetilde{\Gamma}, -\Delta)$, then from (ii) we have

$$\begin{aligned} \gamma - \Gamma = max(\widetilde{\Gamma} - \Gamma, -\Delta - \Gamma) < 0 \quad &\Rightarrow \quad \mu_2 = 0, \\ \widetilde{\Delta} + \gamma = max(\widetilde{\Gamma} + \widetilde{\Delta}, \widetilde{\Delta} - \Delta) < 0, \quad &\Rightarrow \quad \mu_3 = 0, \end{aligned}$$

and therefore, from (i) it yields

$$\begin{aligned} &- \mathscr{A}' + \mathscr{B}' - \mu_1 - \mu_4 = 0, \\ \Rightarrow \quad &0 \leq \mu_1 + \mu_4 = -\mathscr{A}'(\Lambda + \gamma - E) + \mathscr{B}'(\Psi - \gamma - Z). \end{aligned}$$

Note that $-\mathscr{A}' + \mathscr{B}'$ is due to Assumption 5.2.1 strong and monotonically decreasing with respect to γ. And o^* is the point fulfills the condition $\mathscr{A}'(\Lambda + o^* - E) = \mathscr{B}'(\Psi - o^* - Z)$, then we have $o^* \geq max(\widetilde{\Gamma}, -\Delta)$.

In case of $\gamma = min(\Gamma, -\widetilde{\Delta})$, then from (ii) we have

$$\begin{aligned} \widetilde{\Gamma} - \gamma = \widetilde{\Gamma} + max(-\Gamma, \widetilde{\Delta}) = max(\widetilde{\Gamma} - \Gamma, \widetilde{\Delta} + \widetilde{\Gamma}) < 0 \quad &\Rightarrow \quad \mu_1 = 0, \\ -\gamma - \Delta = max(-\Gamma, \widetilde{\Delta}) - \Delta = max(-\Gamma - \Delta, \widetilde{\Delta} - \Delta) < 0 \quad &\Rightarrow \quad \mu_4 = 0, \end{aligned}$$

and therefore, from (i) it yields

$$\begin{aligned} &- \mathscr{A}' + \mathscr{B}' + \mu_2 + \mu_3 = 0, \\ \Rightarrow \quad &0 \leq \mu_2 + \mu_3 = \mathscr{A}'(\Lambda + \gamma - E) - \mathscr{B}'(\Psi - \gamma - Z). \end{aligned}$$

Analogically, $-\mathscr{A}' + \mathscr{B}'$ is strong and monotonically decreasing with respect to γ, and therefore we have $o^* \leq min(\Gamma, -\widetilde{\Delta})$.

In case of $\gamma \in (\widetilde{\Gamma}, \Gamma)$ and $\gamma \in (-\Delta, -\widetilde{\Delta})$, then according to Assumption 5.2.1 we have

$$\gamma \in (max(\widetilde{\Gamma}, -\Delta), min(\Gamma, -\widetilde{\Delta})).$$

Then from (ii) it yields

$$\begin{aligned} \gamma \in (\widetilde{\Gamma}, \Gamma) \quad &\Rightarrow \quad \mu_1 = \mu_2 = 0, \\ \gamma \in (-\Delta, -\widetilde{\Delta}) \quad &\Rightarrow \quad \mu_3 = \mu_4 = 0. \end{aligned}$$

Hence, we have

$$\begin{aligned} &\mathscr{A}'(\Lambda + \gamma - E) = \mathscr{B}'(\Psi - \gamma - Z), \\ \Rightarrow \quad &\gamma = o^*. \end{aligned}$$

Similarly, by using the same argument it is not difficult to show that the following cases do no exist:

$$\begin{aligned} \widetilde{\Gamma} < -\Delta \quad &\text{and} \quad \gamma \in [\widetilde{\Gamma}, -\Delta); \\ -\Delta < \widetilde{\Gamma} \quad &\text{and} \quad \gamma \in [-\Delta, \widetilde{\Gamma}); \\ \Gamma > -\widetilde{\Delta} \quad &\text{and} \quad \gamma \in (-\widetilde{\Delta}, -\Gamma]; \\ -\widetilde{\Delta} > \Gamma \quad &\text{and} \quad \gamma \in (\Gamma, -\widetilde{\Delta}]. \end{aligned}$$

Therefore, the optimization problem of (5.2) can be solved at the point

$$\bar{\gamma} = min(o^*, min(\Gamma, -\widetilde{\Delta})) \vee max(\widetilde{\Gamma}, -\Delta),$$

where o^* denotes the unconstrained strategy, which fulfills the condition $\mathscr{A}'(\Lambda + o^* - E) = \mathscr{B}'(\Psi - o^* - Z)$.

To show the existence of the market equilibrium, consider the aggregated planer problem expressed in all individual constraints given by (5.3), which is also equivalent to (5.1). The problem fulfills the Slater's conditions. Hence, it has optimal primal and dual solutions $(\bar{\phi}^i, \bar{\gamma}^i, \bar{\theta}^i, \bar{\delta}^i)$, $(\bar{A}, \bar{B})$ and the strong duality holds. The optimal value of (5.1) is denoted by p^*, then the weak duality implies that:

$$\begin{aligned} &\sup_{(A,B)\in\mathbb{R}^2} \left(\inf_{(\phi^i,\gamma^i,\theta^i,\delta^i)\in S} \left(\sum_i \mathscr{L}^{A,B,i}(\phi^i, \gamma^i) + \sum_j \mathscr{M}^{A,B,j}(\theta^j, \delta^j) \right) \right) \\ = &\sup_{(A,B)\in\mathbb{R}^2} \left(\sum_i \inf_{(\phi^i,\gamma^i)\in S^i} \mathscr{L}^{A,B,i}(\phi^i, \gamma^i) + \sum_j \inf_{(\theta^i,\delta^i)\in S^j} \mathscr{M}^{A,B,j}(\theta^j, \delta^j) \right) \\ = &\sum_i \left(\inf_{(\phi^i,\gamma^i)\in S^i} \mathscr{L}^{\bar{A},\bar{B},i}(\phi^i, \gamma^i) \right) + \sum_j \left(\inf_{(\theta^i,\delta^i)\in S^j} \mathscr{M}^{\bar{A},\bar{B},j}(\theta^j, \delta^j) \right) \\ \leq &\sum_i \mathscr{L}^{\bar{A},\bar{B},i}(\bar{\phi}^i, \bar{\gamma}^i) + \sum_j \mathscr{M}^{\bar{A},\bar{B},j}(\bar{\theta}^j, \bar{\delta}^j) \\ = &p^*. \end{aligned}$$

Due to the strong duality, the inequality holds with equality as well, so we also have:

$$\begin{aligned}
&\sum_i \mathscr{L}^{\bar{A},\bar{B},i}(\bar{\phi}^i,\bar{\gamma}^i)+\sum_j \mathscr{M}^{\bar{A},\bar{B},j}(\bar{\theta}^j,\bar{\delta}^j)\\
=&\sum_i \inf_{(\phi^i,\gamma^i)\in S^i} \mathscr{L}^{\bar{A},\bar{B},i}(\phi^i,\gamma^i)+\sum_j \inf_{(\theta^i,\delta^i)\in S^j} \mathscr{M}^{\bar{A},\bar{B},j}(\theta^j,\delta^j)\\
\le&\sum_i \mathscr{L}^{\bar{A},\bar{B},i}(\phi^i,\gamma^i)+\sum_j \mathscr{M}^{\bar{A},\bar{B},j}(\theta^j,\delta^j).
\end{aligned}$$

Thus we have

$$\begin{aligned}
\mathscr{L}^{\bar{A},\bar{B},i}(\bar{\phi}^i,\bar{\gamma}^i)&\le \mathscr{L}^{\bar{A},\bar{B},i}(\phi^i,\gamma^i),\\
\mathscr{M}^{\bar{A},\bar{B},j}(\bar{\theta}^j,\bar{\delta}^j)&\le \mathscr{M}^{\bar{A},\bar{B},j}(\theta^j,\delta^j),
\end{aligned}$$

and the existence of the market equilibrium is proved.

□

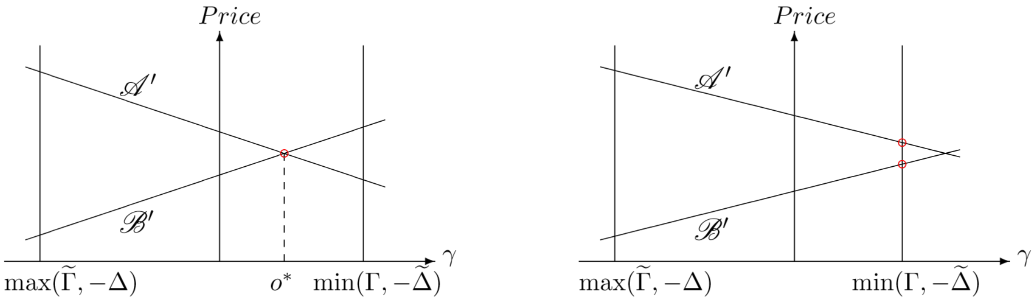

Figure 5.1: Price convergence behavior in a bilateral linking system

Figure 5.1 illustrates the price convergence behavior in a bilateral system. In the case of bilateral-linking, emission allowance permits will flow from the low to the high price regime. This will cause a price convergence towards each other until they coincide, as long as the transfer volume is sufficient as illustrated in the first case. For a linking system with import limits or trade restrictions, the different prices in each ETS will still move towards each other until the point where the maximum allowable permits have been transferred. If this occurs before the prices coincide, there will be two different prices in each trading scheme as shown in the second case.

5.3 Model of Unilateral Systems

Unlike the bilateral linking system, a unilateral system allows allowance permits to be traded only in one direction. In case that different prices of permits are traded in both markets, a price convergence behavior is also expected and its corresponding equilibrium model is to be developed in this section.

5.3.1 Model description

Suppose that the administrator of ETS1 establishes a unilateral link with ETS2 and accepts allowance permits from ETS2 for the compliance purpose of their agents. However, it is not possible for agents in ETS2 to use permits form ETS1 for their compliance. Intuitively, based on the model results of a bilateral system in the previous section, one can expect that the allowance price converges uni-directionally.

In this case, all definitions of permit prices A, B, agents $i \in I, j \in J$, their emissions E^i, Z^j, allocated allowances Λ^i, Ψ^j, and internal trading positions ϕ^i, θ^j remain the same as defined in the previous section. Since allowances can only flow in one direction, the potential trading volumes $\phi^i \in \mathbb{R}$ and $\theta^j \in \mathbb{R}$ from ETS2 to ETS1 have the following constraints:

$$0 \leq \gamma^i \leq \Gamma^i, \qquad \widetilde{\Delta}^j \leq \delta^j \leq 0.$$

The net amount of agents α^i and β^j remain the same, so that the formulations of their projected Profit-and-Lost functions $\mathscr{A}^i(\alpha^i)$ and $\mathscr{B}^j(\beta^j)$ as well as the cost functions $\mathscr{L}^{A,B,i}(\phi^i, \gamma^i)$ and $\mathscr{M}^{A,B,j}(\theta^j, \delta^j)$ are unchanged. For equilibrium modelling consider the assumption as follows:

Assumption 5.3.1. *(i)* $\alpha^i \mapsto \mathscr{A}^i(\alpha^i)$ *and* $\beta^j \mapsto \mathscr{B}^j(\beta^j)$ *are monotonically increasing, concave and continuously differentiable for* $i \in I$ *and* $j \in J$.
(ii) $\Gamma^i > 0$*, for all* $i \in I$. $\widetilde{\Delta}^j < 0$*, for all* $j \in J$.

Let $S^i = \mathbb{R} \times [0, \Gamma^i]$ and $S^j = \mathbb{R} \times [\widetilde{\Delta}^j, 0]$ be the feasible compliance strategies of any agent i and j, respectively. And $S = \{(\phi, \gamma, \theta, \delta) | (\phi^i, \gamma^i) \in S^i, (\theta^j, \delta^j) \in S^j, \forall i \in I, j \in J\}$ be the feasible compliance strategy for the overall market. Furthermore, Definition 5.2.1 is also used for the unilateral system and prices

$(A^*, B^*) \in \mathbb{R}^2$ together with the compliance strategy $(\phi^*, \gamma^*, \theta^*, \delta^*) \in S$ form a market equilibrium.

Keeping the notations of aggregated amount $\gamma, \delta, E, Z, \Lambda, \Psi, \Gamma, \Delta, \alpha, \beta, \mathscr{A}(\alpha)$, and $\mathscr{B}(\beta)$ unchanged as defined in the previous section. Under the model assumptions, the optimization problem for a representative planer can be expressed as

$$\inf \quad \left(\sum_{i \in I} \mathscr{L}^{A,B,i}(\phi^i, \gamma^i) + \sum_{j \in J} \mathscr{M}^{A,B,j}(\theta^j, \delta^j) \right) \tag{5.4}$$

with constraints $0 \leq \gamma \leq \Gamma, \widetilde{\Delta} \leq \delta \leq 0$ and $-\gamma = \delta$. And the optimization problem can be also reformulated as:

$$\begin{aligned} \inf_\gamma \quad & (-\mathscr{A}(\Lambda + \gamma - E) - \mathscr{B}(\Psi - \gamma - Z)) \\ s.t. \quad & 0 \leq \gamma \leq \Gamma, \quad 0 \leq \gamma \leq -\widetilde{\Delta}. \end{aligned} \tag{5.5}$$

5.3.2 Model results

Similarly, the problem of market equilibrium (5.5) is a convex optimization problem and its optimal solution $\bar{\gamma}$ is given as a solution to the KKT condition. The following proposition can be proved:

Proposition 5.3.1. *Let $\bar{\gamma}$ be an optimal solution for the representative problem. Then*
(i) the market equilibrium exits.
(ii) the equilibrium allowance prices in ETS1 and ETS2 are given by

$$A = \mathscr{A}'(\Lambda - E + \bar{\gamma}), \quad B = \mathscr{B}'(\Psi - Z - \bar{\gamma}).$$

Proof. Only the proof idea will be provided. The optimization problem fulfills Slater's condition and therefore its optimal solution is given as a solution to the KKT conditions given by

(i) Stationary condition:

$$-\mathscr{A}'(\Lambda + \gamma - E) + \mathscr{B}'(\Psi - \gamma - Z) - \lambda_1 + \lambda_2 + \lambda_3 = 0.$$

(ii) Complementary slackness condition:

$$\lambda_1\gamma = 0, \quad \lambda_2(\gamma - \Gamma) = 0, \quad \lambda_3(\gamma + \widetilde{\Delta}) = 0.$$

(iii) Primal feasibility:

$$-\gamma \leq 0, \quad \gamma - \Gamma \leq 0, \quad \gamma + \widetilde{\Delta} \leq 0.$$

(iv) Dual feasibility:

$$\lambda_1 \geq 0, \quad \lambda_2 \geq 0, \quad \lambda_3 \geq 0.$$

Solving this problem, it is not difficult to see that

$$\bar{\gamma} = max(0, min(o^*, \Gamma))$$

is the optimal solution, where o^* fulfills the condition $\mathscr{A}'(\Lambda - E + o^*) = \mathscr{B}'(\Psi - Z - o^*)$. Therefore, o^* determines the optimal trading volume from ETS2 to ETS1 and the corresponding allowances permit price is determined as well. The proof of existence of the market equilibrium is similar as the proof for the bilateral system.

□

Intuitively, the market will find the optimal trading volume between the two markets, and the price of allowance will converge in both market. However, if one of the constraints of trading volume is reached, the price movement in each system will be stopped and there will be different prices in each markets. In case of simplicity, suppose $\Gamma \leq \widetilde{\Delta}$. We plotted in Figure 5.2 the price convergence for this situation. The price behavior is basically quite similar as in the previous case for the bilateral system. Since the transfer of allowances occurs unidirectional, the opposite direction for the flow is not allowable. If the transfer direction is from the high-price scheme to the low-price scheme, then no transfer will take place as shown in the last case. However, this case can be considered as a special case in the bilateral system with zero transfer limit regulation.

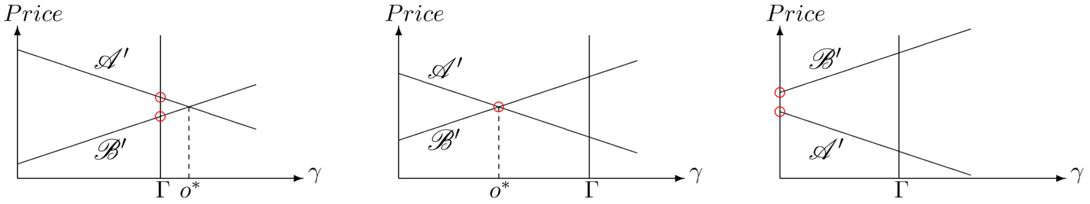

Figure 5.2: Price convergence behavior in a unilateral linking system

5.4 International Background and Outlook

The purpose of linking emission trading systems, either domestically or internationally, is to establish a larger carbon market and form a uniform price for emissions. The benefits of creating larger market is obvious. First, it helps to achieve emission abatement in a cost efficient way. Market participants in the system with higher abatement costs will flow to the one with lower abatement costs automatically. Second, a larger carbon market will provide better liquidity and therefore reduce the price volatility. Finally, merge different international markets will help to create a single price in both of the systems, weaken the competitiveness, so that the risk of carbon leakage can be reduced or even avoided. Therefore, with more emission trading systems emerging worldwide, linking systems are also implemented and more discussions on this issue are brought on the table.

Generally, linking can be categorized into bilateral and unilateral mechanisms, depending on the way how carbon certificates are permitted to flow between the systems. Currently, there are already implemented linking systems and systems in plan.

Key implemented linking systems

The Regional Greenhouse Gas Initiative (RGGI) is the first emission trading programme in the United States, started with its first three-year compliance period in 2009. It includes the states of Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont. The programme is set up through a memorandum of understanding as a combination of nine individual ETSs that are linked with each other directly. Each participating state has its own regulation based on the Model Rule provided by RGGI.

California's cap-and-trade programme came into force officially on 1 January 2013, although the auction for California Carbon Allowances (CCAs) was held earlier in November 2012. At the same time, Quebec's cap-and-trade programme was also launched. As of 1 January 2014, Quebec's bilateral linkage with California's cap-and-trade programme allows regulated entities to trade carbon permits across both jurisdictions. In this linkage, participants in each market can use both emission allowances and offsets issued by either Quebec or California.

The use of international credits from Kyoto Protocol by the EU ETS can be also seen as an indirect unilateral link, since emission reduction projects of CDM and JI and EU ETS have mutual recognition of their carbon certificates created by them. The legal foundation of using international credits is the Linking Directive adopted in 2004 (EU 04), in which the EU allows the limited use of offset credits from JI and CDM projects to be used to cover emissions in the EU. Since then, operators of EU ETS begin to invest in the CDM projects. And this results 670 million CERs of 1.06 billion international credits in total used during the second trading phase. Therefore, in the third trading phase, the use of international credits is under regulated more stringently. As a result, the demand for CERs dropped drastically and this caused the priced collapse of CERs.

Indirect unilateral link are also between CDM and JI projects and the New Zealand emissions trading system. Since the beginning of the scheme in 2010, around 90% of units surrendered to meet New Zealand ETS obligations were from the international credits. With no restrictions on the quantum of international units, it resulted in a large bank of allowances of the domestic trading system.

Key linking systems in plan

Western Climate Initiative (WCI), established in 2008, is a North American regional initiative including the US State of California and the Canadian provinces Quebec, British Columbia, Ontario and Manitoba. It aims to provide administrative and technical services to support the implementation of regional emissions trading schemes and to facilitate future linkage between the schemes.

Currently only California and Quebec linked their emission trading systems since 2014. Ontario planed to link their cap-and-trade programme with the existing linking system in its early years. Manitoba announced the implementation of an ETS that will be designed to be linked with the existing California and Quebec systems at the COP 21.

The Swiss ETS started in 2008 with a five-year voluntary phase, where emission allowances are traded only on a voluntary basis. Since January 2013, revised regulations entered into force in the Swiss ETS and the system became mandatory, mainly for the domestic energy intensive sector. Switzerland is currently negotiating with EU on linking both of their emission trading systems bilaterally. To achieve this purpose, many elements of the Swiss ETS have been designed to match provisions of the EU ETS from 2013.

China launched 7 pilot emission trading schemes in different provinces and cities from 2013 to 2015 as a part of its 12th Five-Year Plan ran from 2011 to 2015. A national ETS is planned to be established in the second half of 2017 by the National Development and Reform Commission (NDRC), the central regulator of the upcoming national ETS. With the establishment of the Chinese national ETS, it will be potentially the worlds largest emission trading system and will cover around 50% of total domestic emissions, accounts for around 12% of total global emissions. To establish the national ETS, one significant issue is to build multilateral link to all pilot markets and connect them to the national ETS as well. The NDRC is coordinating with different stakeholders in designing such domestic linking system. Besides, the NDRC is exploring the possibility of linking the national ETS with other ETSs around the world at an appropriate time in the future.

6

Conclusion

6.1 Results of the thesis

Global warming due to the increase in anthropogenic greenhouse gases has gained wide consensus from the scientific community. To stabilize the greenhouse gas concentrations in the atmosphere, market-based policy instruments are considered as effective solutions. Among these, the cap-and-trade systems are very popular and have been established over the globe. In most carbon markets, the European Union Emission Trading Scheme (EU ETS) has the largest scale and its benchmark product, the EUA futures contract, is largely traded. Research on EUA price behavior is therefore an important topic.

In the present research for pricing the carbon permits, martingales finishing at two-valued random variables can be considered as an useful tool to evaluate the risk neutral futures price dynamics of EUA, since it is able to cover most important regulations of EU ETS. From the original studies of Carmona and Hinz in (CarH 11), a reduced-form model for two-valued martingales is flexible in terms of time- and space changing volatility and supposed to be capable to match the observed historical or implied volatility of the underlying futures contract. A crucial step in the calibration of the model is to transform the observed futures prices into a Gaussian process by changing the probability measure.

However, statistical tests show non-Gaussian property of such a Gaussian process. This gives us the idea to extend the model by taking into account a dynamic market price of risk in order to improve the calibration quality. By applying a bivariate model with a time series for the implied market price of risk, it is able to calibrate the extended model with extensive historical traded data. Generally, futures prices of carbon permits carry forward-looking information of market participants and this information can be revealed by the values of the risk premia the investors attach to the carbon certificates. Estimate results of the bivariate model show a negative correlation between the futures prices and the risk premia. This reflects the fact that the more risky the investment in EUA futures is, the higher the additional expected rate of return should be. Therefore, in order to achieve a higher required rate of return, the EUA futures must be discounted and thus sold at a lower price to investors.

Moreover, EUA options written on the futures are traded for many years although no theoretical foundation for their pricing is available yet. The bivariate model provides also option valuation schemes. The option price formula derived in Chapter 4 is not available in a closed form, but can be applied simply by using numerical integration. Compared with the original model with constant market price of risk, it can be found that EUA option prices are underestimated before a certain time point and then overestimated after that time point. This is because the implied risk premia increase with time and will exceed their average level to a certain time. Thereafter, asset prices must be discounted to compensate the relative higher risk for investors.

Follow the basic idea that allowance prices should be explained as the probability of shortage multiplied by the penalty studied by Carmona et al. in (CFHP 10), it is possible to derive the spot price of emission certificates by modelling the cumulative emission process. For this purpose, some appropriate estimation methods have to be applied. (CheT 12) and (GruK 10) performed some approximation approaches to model the emission rate, then the cumulative emissions are given by the integration on the rate. This thesis discussed another approximative approach by modelling the emission process directly via looking into a stochastic subordinator. Under concrete model assumptions, the spot price of permits can be derived in a simple form. However, appropriate parameter estimation methods are required for further use.

Looking at the issue of emission trading from an international perspective, linking emission trading systems has become significant since more cap-and-trade systems are already launched or are planned to be established over the globe. Linkage under different regulations could cause different price behavior. Their qualitative analysis has been conducted by Grüll and Taschini in (GruT 12). This thesis develops a market equilibrium model on deterministic settings and investigates the price convergence behavior of carbon certificates in trading schemes to be linked. The model results coincide with the qualitative analysis of Grüll and Taschini. It shows that under unlimited trading restrictions, permit prices will converge to a single one. But in the presence of trading restrictions, different prices will move towards each other until the maximum allowable trading volume has been transferred. If this happens before the two prices converge, the result will be two differently-priced schemes with no flow of permits between them.

6.2 Key findings

Key findings of the thesis include:

- Stochastic reduced form model is proven to be useful to model the allowance permit prices observed in the trading market of EU ETS. Especially the model based on a two-valued martingale forms the risk neutral futures price dynamics and captures the main properties of the market mechanism.

- To evaluate the return that the market wants as compensation for taking the risk, it is possible to extract the information of the market price of risk by applying an extended pricing model.

- The EUA option price can be derived by the extended model, carrying extra information of a dynamic, time-varying market price of risk.

- EUA futures price can be modeled by modelling the aggregative cumulative emissions directly. However, appropriate parameter estimate method has to be determined.

- Price behavior of linking systems can be explained quantitatively by a static equilibrium model. Prices in different trading schemes will converge unless special constraints are set, such as limiting the transaction volume between the schemes.

6.3 Further research

Based on the current results of this thesis, further research activities can be focused from the following aspects:

- The allowance permit price dynamics of EU ETS can be analyzed based on the current basic model, but capturing more properties of the market design, such as including the potential effects of the market stability reserve.
- Pricing model of a linking system can be investigated in a dynamic framework, in which price development can be studied during runtime.
- Furthermore, some fundamental analysis on the price modelling can be conducted by examining the related economic, financial and other qualitative and quantitative factors affecting the EUA prices. This would be a helpful supplement to the financial modelling of emission allowance prices.

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