Master Thesis Report

How to make the carbon offsets mechanism work in the current phase of the EU ETS?

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Challenge the future

Master thesis final report

How to make the carbon offsets mechanism work in the current phase of the EU ETS?

by

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Executive Summary

The end of the 20^{th} century and the beginning of the 21^{st} have been confronted with the already palpable consequences of climate change. According to the scientific community, climate change is mainly due to the exponential increase of anthropogenic Greenhouse Gas (GHG) emissions in the atmosphere since 1850. Switching rapidly from fossil fuels to Renewable Energies (RE) can be key to decrease GHG emissions and therefore slow down climate change. Even though RE do compete economically with fossil fuels, energy investments are still dominated by fossil fuels. Environmental policies can therefore help to decrease investments in RE. In particular, carbon pricing is an environmental policy that can be used to foster RE's deployment. Indeed, setting a carbon price conveys the signal that long-term investments should be switched from high-emitting sources (like fossil fuels) to low-carbon technologies and especially to RE. The higher the carbon price is, the more powerful is the signal to switch to low-carbon technologies.

Carbon pricing is defined using a carbon tax, an Emissions Trading Scheme (ETS) or a combination of the both. This Master Thesis only focuses on ETSs. In a few words, an ETS is defined on specific industrial sectors by a regulator which sets an overall emissions target for those covered sectors over a given period. The ETS's regulator issues the same amount of permits as its emissions target, in tonnes CO_2 equivalent ($tCO_{2,eq}$), since one permit is equivalent to one $tCO_{2,eq}$, over this period. A firm under the ETS has to possess at least as many permits as its emissions (in $tCO_{2,eq}$) over this period. In addition, the ETS's regulator has to decide whether it allows the use of offset credits from uncovered sectors as compliance units. An offset credit is the carbon unit derived from a crediting mechanism. It corresponds to the reduction of one $tCO_{2,eq}$ by a project. This one $tCO_{2,eq}$ reduction can be turned into an offset credit if the project is recognized by a crediting mechanism. Allowing offset credits on an ETS means that a firm under the ETS can either

use permits or offset credits to cover its emissions. Allowing offset credits is an interesting option for ETS's regulator because it expands abatement options. Nevertheless, allowing the use of offset credits has its shortcomings: it increases the amount of compliance units on the ETS, when most of the ETSs are already facing an oversupply of permits. Because of those oversupplies of permits and offset credits units, the concerned ETSs face low permit and offset credit prices. Low permit prices imply that covered firms will have less incentive to reduce their emissions and to switch from high-emitting to low-emitting technologies. The above mentioned issues faced by the ETSs will be detailed through the analysis of the European Union Emissions Trading System (EU ETS). This leads us to the following crucial research question: how could ETSs efficiently define their carbon offset market? A carbon offset market is considered efficiently defined when it enables to achieve the highest society welfare. Welfare is defined as the society benefits minus the society costs of implementing such policy. Moreover, this carbon offset market should generate high permit prices, thus promoting RE investment.

Three offset policy instruments are therefore introduced in this Master Thesis to define more efficiently a carbon offset market. These policy instruments stem from a paper written by Bento et al. (2015). Their impact is evaluated using an economic model, based on the one developed by Bento et al. (2015), which models an ETS linked to a carbon offset market. The carbon offset market is assumed to function as a Sectoral Crediting Mechanism (SCM). A SCM works as follows: a regulator sets the same baseline for each firm of a specific sector. If a firm's emissions are under the baseline, the firm can sell as offset credits the difference between the baseline and its emissions, in $tCO_{2,eq}$. The three offset policy instruments implemented are:

- setting a stricter baseline;
- using a trade ratio converting one offset credit into more/less than one permit (one permit is equivalent to one credit divided by the trade ratio);
- imposing a limit on the amount of offset credits that can be sold to ETS's firms.

The model is then simulated using EU ETS data to see how the three policy instruments should be combined in order to reach the maximum society welfare.

The conclusions to be drawn from the economic model's simulations are that a baseline at its lowest value should be combined with a trade ratio higher than 1 and a non-binding limit (this case is called the "Unrestricted" case). Indeed, this combination results in the higher society welfare. It also achieves the highest emissions abatement. Finally, it results in a quite high permit price, approaching 26 $€/tCO_{2,eq}$. This permit price is lower than for the "No offsets" simulation, for which the permit price is equal to 40 $€/tCO_{2,eq}$ (case when offsets are not allowed on the EU ETS). However, the "No offsets" case results in a welfare two times smaller than the one of the "Unrestricted" case. It is also interesting to compare the "Unrestricted" case with the "Alike situation" case. In the "Alike situation" simulation case, the three policy instruments are set to approximate the current EU ETS's offsets policy instruments. The trade ratio is set to 1 (since it is non-existent in the current EU ETS), the limit is set as currently in the EU ETS and the baseline is set at its mean value. This offset policy instruments setting does not only result in a low society welfare, but also in a low permit price, equal to 2.3 $€/tCO_{2,eq}$. This illustrates that the EU ETS should redefine its offsets policy instruments.

The European Commission (EC) did not state yet if it will allow the use of offset credits once the use of international offset credits by 2021 is forbidden. Indeed, the EC has a domestic emissions reduction target after 2021 and decided not to allow international offset credits anymore then. Assuming the EC wants to increase society's welfare while taking the environment into account, based on the achievements of this Master thesis, two recommendations can be made to the EC:

- First, the EU ETS should define a domestic carbon offset market. It is said domestic because it has to be defined within European Union (EU)'s sectors (since the EU has a domestic emissions reduction target). Even if the EU ETS's carbon offset credits market was modeled in this Master thesis as a sectoral mechanism, others mechanisms could also be used. We cannot therefore advocate for a particular carbon offset market mechanism;
- Second, the amount of offset credits entering the EU ETS market should be limited using additional policy instruments, so the permit price does not drop too much.

Acronyms

BAU	Business As Usual
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
COP	Conference of the Parties
EC	European Commission
EEA	European Environment Agency
ETS	Emissions Trading Scheme
EU	European Union
EU ETS	European Union Emissions Trading System
GHG	Greenhouse Gas
IET	International Emissions Trading
IPPC	Intergovernmental Panel on Climate Change
JI	Joint Implementation
MACC	Marginal Abatement Cost Curves

MCA	Marginal Cost of Abatement
MRV	Monitoring, Reporting & Verification
MSR	Market Stability Reserve
NDC	Nationally Determined Contribution
R&D	Research & Development
RE	Renewable Energies
SCC	Social Cost of Carbon
SCM	Sectoral Crediting Mechanism
SET	Sustainable Energy Technologies
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
US EPA	US Environmental Protection Agency

Glossary

Back-loading	Delays the auction of some permits.
Banking	Allows offset credits/permits to be saved for future phases.
Carbon leakage	Happens when a firm relocates its activities due to too high environmental policies compliance costs.
Compliance unit	A compliance unit is a carbon unit that is recognized as equivalent to a permit.
Grandfathering	A firm freely receives an amount of permits proportional to its past emissions.
Offset credit	An offset credit is the carbon unit derived from a crediting mechanism. An offset corresponds to the reduction of one $tCO_{2,eq}$ by a project. This offset can be turned into an offset credit if the project is recognized by a crediting mechanism. This offset credit can then be used in some ETSs that consider it as a compliance unit.
Opt-in	A firm is said to opt-in when it decides to join a crediting mechanism and asks for offset credits.
Permit	A permit is the carbon unit derived from a trading mechanism (or ETS). Firms under an ETS have to hold a permit for each unit of $tCO_{2,eq}$ they emit.
Under-credited emissions	A firm is said to have under-credited emissions reductions when it achieves emissions reductions but cannot convert them into offset credits.

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Chapter 1

Introduction

Since 1850 and the industrial revolution, demand for energy constantly increased and, with it, global welfare and economic development. This exponential economic development has been based, since then, on a wider and wider use of fossil fuels. These sources of energy have made the substitution of man's work by machines possible, thus increasing the production of goods. But fossil fuels' use did not come only with benefits: they are responsible for the major part of anthropogenic Greenhouse Gas (GHG) emissions in the atmosphere, which tends to accelerate the current climate change according to the Intergovernmental Panel on Climate Change (IPPC): "Most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations." (Rogelj et al., 2018). Lately, climate change has been more and more in the spotlight and numerous actions have been taken to tackle it. Even though, it keeps affecting more and more people every year and the list of climate catastrophes sets records every year. In 2018, around 5,000 people died and 28.9 million required emergency assistance as a result of extreme climate events (Guardian, 2018).

Multiple solutions already exist to tackle climate change: increasing energy efficiency, reducing energy demand, switching from fossil fuels to Renewable Energies (RE), using Carbon Capture and Storage (CCS), etc. This study will focus solely on Sustainable Energy Technologies (SET)'s and Renewable Energies (RE)' development. SET is an energy that helps meet the energy demand of today without compromising the energy demand of people in the future. RE is an energy that is naturally regenerated with time.

Indeed, switching rapidly from high-emitting technologies to Sustainable Energy Technologies and in particular Renewable Energies can be key to decrease GHG emissions and therefore slow down climate change. Although RE can already compete economically with fossil fuels, investments in energy are still mainly made in fossil fuels plants. RE's deployment and financing therefore requires governmental support.

One of the policies that can be used to promote RE investments consists in putting a price (preferably a high one) on carbon. This is done using either a carbon tax, an Emissions Trading Scheme (ETS) or a combination of the two. ETS will be at the heart of this study. In an ETS, also called trading mechanism, a regulator sets an emissions reduction target for specific industrial sectors over a given period of time. This emissions reduction target is converted into permits[1], one permit being equivalent to one tonne CO_2 equivalent ($tCO_{2,eq}$). Firms under the ETS are under the obligation to possess a number of permits at least equal to or higher than their emissions. The regulator can also decide to authorize covered firms to use offset credits[2]. Indeed, allowing offset credits on the ETS can help capped sectors[3] reaching their emissions reduction target at lower costs. An offset credit is the carbon unit derived from a crediting mechanism. Different crediting mechanisms exist.

The Kyoto Protocol highly helped in developing carbon markets. It defined in 1997 three carbon markets mechanisms: the International Emissions Trading (IET), the Clean Development Mechanism (CDM) and the Joint Implementation (JI). The IET is a cap-and-trade mechanism, according to which countries that have emissions reduction targets under the Kyoto Protocol (Annex B countries[4]) can trade their emissions permits to fulfill their targets. The CDM and the JI are both crediting mechanisms. Among others, the European Union followed the trend and decided a few years later, in 2005, to start its own cap-and-trade mechanism, the European Union Emissions Trading System (EU ETS), the world's largest carbon market (Newell et al., 2014). Since its implementation, the EU ETS, as any other carbon markets, have been highly criticized (Branger et al., 2015). It mainly faced low permits'

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[1] Permit: A permit is the carbon unit derived from a trading mechanism (or ETS). Firms under an ETS have to hold a permit for each unit of $tCO_{2,eq}$ they emit.

[2] Offset credit: An offset credit is the carbon unit derived from a crediting mechanism. An offset corresponds to the reduction of one $tCO_{2,eq}$ by a project. This offset can be turned into an offset credit if the project is recognized by a crediting mechanism. This offset credit can then be used in some ETSs that recognize it as a compliance unit.

[3] Sectors that are under a trading mechanism are referred to as capped sectors.

[4] Parties that are part of the UNFCCC are categorized as the following: Annex I are industrialized Parties, Annex B are countries that were committed to emissions reduction under the Kyoto Protocol and non-Annex I countries are mostly low income countries.

price (along with a permits' price volatility) and an oversupply of permits and offset credits. The EU ETS is currently in its 3rd phase. Several measures have been taken for its 4th phase to address the EU ETS's issues and decrease the amount of permits/offset credits on the market. Among others, the emissions reduction target will be increased from 1.74% currently to 2.2% by 2021 and the system of free allocation will be revised (less sectors will see their permits freely allocated/grandfathered[5]). The two main changes remain the implementation of a Market Stability Reserve (MSR) and the no longer use of international offset credits (such as the ones of the CDM and the JI) (European Commission, 2018c).

Yet, this Master thesis supports the use of offset credits by the EU ETS once it bans international offset credits from the CDM and the JI. This thesis will therefore try to evaluate how the EU ETS could efficiently define a "new" offset credits market. This offset credit market will be assumed to be based on a Sectoral Crediting Mechanism (SCM). A SCM is a baseline-and-credit scheme which sets the same baseline for every firms of a specific sector. Firms that choose to opt-in[6] can sell offset credits to capped firms by decreasing their emissions below the baseline. Three offset policy instruments are introduced to reduce the amount of offset credits on the market and increase the permits price. These three policy instruments originates from a paper of Bento et al. (2015)[7] and are evaluated based on an economic model to see which policy instruments' combination is the most efficient to reduce total emissions (and with it non-additional emissions reduction) and emissions reduction costs while maximizing welfare. Welfare is defined as society benefits minus society costs of implementing a policy measure. The three types of offset policy instruments studied here are: setting a stricter baseline; using a trade ratio converting one offset credit into more/less than one permit (one permit is equivalent to one credit divided by the trade ratio); and finally imposing a limit on the amount of offset credits that can be sold to ETS's firms. The model is simulated using EU ETS data.

To reach the Master thesis objective, a main research question needs to be answered, based on a set of sub-questions.

Main research question:
How to make the carbon offsets mechanism work in the current phase of the EU ETS?

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[5] Grandfathering: A firm freely receives an amount of permits proportional to its past emissions.

[6] Opt-in: A firm is said to opt-in when it decides to join a crediting mechanism and asks for offset credits.

[7] This article will be cited a lot in this Master thesis: as of now it will be referred as "BKL", in reference to the three authors, Bento, Kanbur and Leard.

Sub-questions:
1. *What is the rationale of carbon pricing?*
2. *What are the issues the EU ETS has been facing since its implementation in 2005?*
3. *What policy measures could be implemented to solve the issues due to the EU ETS' carbon offsets mechanism?*
4. *Can the results of Bento et al. (2015) be replicated?*
5. *What adjustments of the model are necessary to reflect the EU ETS' case?*

To answer to the main research question, an analytical model will be developed, based on the one developed by BKL, and simulated using EU ETS data. For simplification, only one sector of the EU ETS will be taken into account: the power sector. It is indeed a key sector for GHG emissions reduction and for RE' integration. The analytical model will be simulated based on EU ETS's 2015 values.

The structure of the report is as follows. In Chapter 2, the rationale of implementing carbon pricing for RE's development is explained. The current EU ETS situation is presented with a focus on the issues it faced since 2005 and measures that could be implemented to solve them. In Chapter 3, an ETS, allowing offset credits is modeled, using some simplifications and assumptions. In Chapter 4, the code (based on the code of BKL) developed for the simulations is detailed. The code is first run with the data used by BKL to compare our results with theirs. The code is then run with EU ETS data and the results are discussed. Chapter 5 concludes the Master thesis by comparing the future measures of the EU ETS' 4th phase and offsets policy measures that were recommended in this study.

Chapter 2

Carbon pricing within the EU

This chapter first discusses the reasons for pricing carbon: as it will be seen, carbon pricing is put in place so damaging economic activities outcomes on the environment and on human beings are taken into account by polluters. The key consequence of introducing a carbon price is that it encourages investments in Sustainable Energy Technologies (SET) and especially in Renewable Energies (RE). Drastically and rapidly developing RE is more than necessary to address climate change according to the Intergovernmental Panel on Climate Change (IPPC)'s 1.5°C report: "by 2050, the share of electricity supplied by renewables [should] increase to 59–97% (minimum-maximum range) across 1.5°C pathways" (Rogelj et al., 2018).

The Chapter then elaborates on how carbon is priced: it can be done through the establishment of an Emissions Trading Scheme (ETS), also called cap-and-trade system, or of a carbon tax or through a combination of both.

Next, the carbon pricing system of the European Union (EU), the European Union Emissions Trading System (EU ETS), as the issues it has faced since its implementation and the measures the European Commission (EC) took to respond to them are presented.

The Chapter concludes on different solutions the EC could implement to solve the latter issues. It could for example introduce a permit's price floor or change the design of its offset credits market.

2.1 Why carbon pricing?

Carbon pricing is a more and more used tool. To date (see Figure 2.1), 51 carbon pricing initiatives have been or are about to be implemented at a national or regional level, representing 25% of worldwide GHG emissions. 26 of them originate from an Emissions Trading Scheme and 25 of them are issued from carbon taxes.

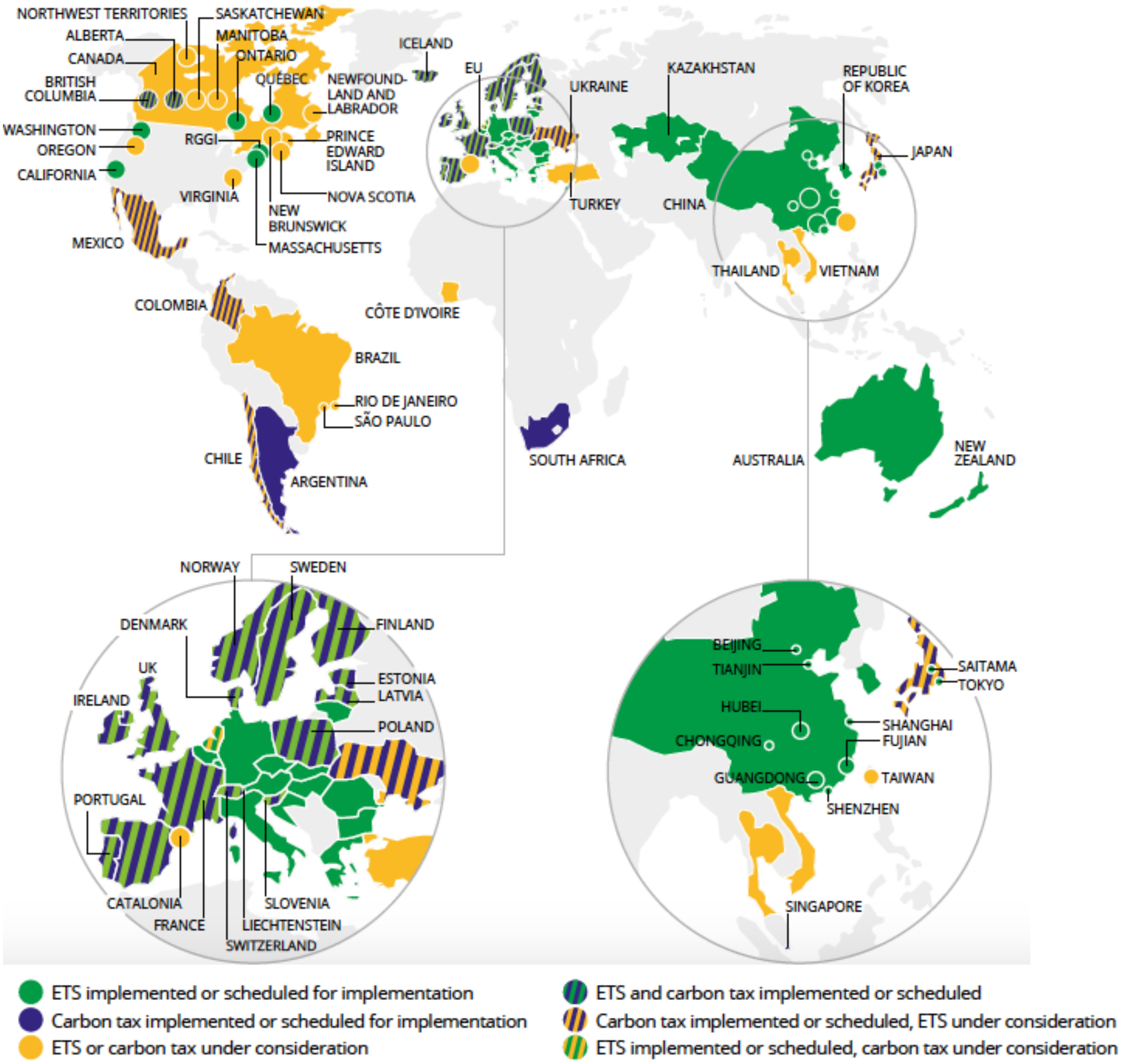

Figure 2.1: Map of carbon pricing policies that have been/are about to be implemented and that are under consideration (ETS and carbon tax) (World Bank and Ecofys, 2018)

2.1.1 Internalizing environmental externalities

Carbon pricing is an environmental policy put in place so damaging outcomes of economic activities on the environment and on human beings are taken into account by polluters. Those damaging consequences are referred to as "externalities". For example, a coal power plant company has an economic incentive to use the right amount of coal for its production, since coal has an economic value. Burning this coal for electricity production however deteriorates the air quality and results in ozone depletion and climate change acceleration. As a consequence, it costs a lot of money to society in healthcare and in mitigation measures to anticipate climate change future damages: this is called the Social Cost of Carbon (SCC), which carbon pricing is supposed to reflect. Until recently, high-emitting companies did not have to deal with those negative consequences. Environmental policies have been therefore developed to require polluters to minimize their environmental externalities: either by internalizing their environmental costs (by putting a price on them) or by putting a limit on the level of environmental pollution allowed. As an example, there are several ways to deal with cars' emissions and reduce them. It can be done through the implementation of a carbon tax on oil to take into account the environmental costs of oil combustion. This puts a burden on the consumers who see the oil's price go up. It can also be done by setting a limit on new cars' emissions rate per km/h. This puts a burden on the cars' manufacturers who have to either improve their technology efficiency, or either switch of technology.

Implementing a carbon price has another very important and positive impact: it fosters the research in technological innovations and especially in Sustainable Energy Technologies (SET). Indeed, many environmental problems have a long-term impact and could be addressed with technological changes such as low carbon technologies. However, market forces alone do not provide enough incentive to implement SET such as energy efficient technologies and RE technologies because investments are still dominated by high-emitting technologies. Implementing a carbon price is a powerful signal for technological changes and, more importantly for Renewable Energies investment (Popp et al., 2010).

2.1.2 A signal for Renewable Energies' investment

When a carbon price p_c is introduced, it affects each emitting company products' price since they now have an additional cost of the form $p_c * e$, where e is their rate of emissions per unit of output. Let's take the example of electricity production. Currently, different types of plants are involved in the process of electricity production: gas, nuclear, coal, oil, hydropower, solar, wind... Each type of plant has a certain emissions rate per unit of output (see Table 2.1).

Table 2.1: Life cycle carbon footprint of different power plants (Turconi et al., 2013)

Energy source	Emissions factor ($gCO_{2,eq}/kWh$)
Hard coal	660–1050
Lignite	800–1300
Natural gas	380–1000
Oil	530–900
Nuclear power	3–35
Biomass	8.5–130
Hydropower	2–20
Solar energy	13–190
Wind	3–41

The power plants can be ranked according to their marginal production costs and the amount of electricity they can deliver: it is called the merit order curve. If there is no carbon price implemented, each power plant's variable marginal costs only depends on its energy source's price (see Figure 2.2).

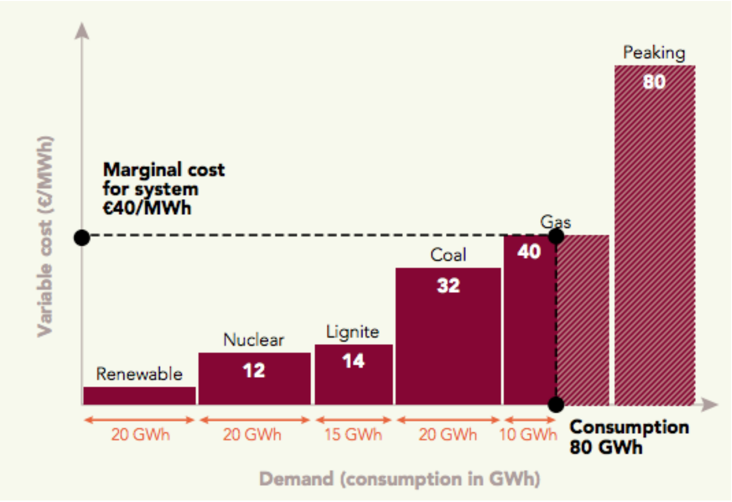

Figure 2.2: Merit order of power plants supplying, as an example, 80 GWh at a carbon price of $0€/tCO_{2,eq}$ (Rte, 2016)

If the carbon is priced, each power plant's variable marginal costs now depends not only on its energy source's price but also on the carbon price (see Figure 2.3). It affects the power plants' merit order:

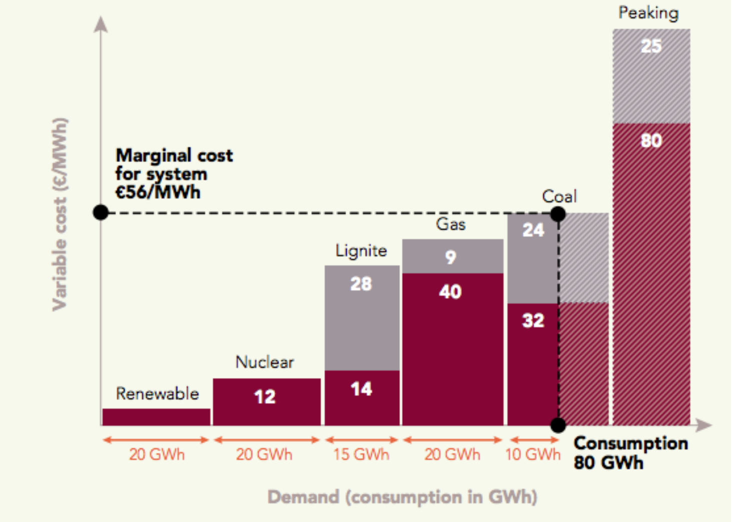

Figure 2.3: Merit order of power plants supplying still 80 GWh at a carbon price of 30$€/tCO_{2,eq}$ (Rte, 2016)

The carbon price does not have any impact on the marginal costs of the RE plants (since they do not emit), but the difference in marginal costs between the fossil fuel plants and the renewable plants is a lot larger than in the 0$€/tCO_{2,eq}$ case. If the carbon price stays high and stable, it gives a good signal for investors that it is now time to invest in renewable energies rather than in fossil fuels.

2.1.3 How to price carbon

Carbon pricing can be either set using a carbon tax (the regulator controls the carbon price) or using a cap-and-trade system (the regulator controls the quantity of emissions).

2.1.3.1 Carbon tax

The concept of a carbon tax is quite simple as taxes are often used by governments on all kind of products. Setting a carbon tax consists in setting a price on carbon (in $€/tCO_2$) that some firms/sectors have to pay relatively to their emissions. There may be different carbon taxes for different sectors.

The firms concerned by the carbon tax will adapt their strategy relatively to the value of the carbon tax and its long-term impact. In this case, the regulator knows with certainty the carbon price but does not know the quantity of emissions that this policy will result in. The regulator has to wait for the market to adapt to the carbon tax to know in which quantity of GHG emissions the carbon tax will result in.

One of the biggest challenge nowadays is to evaluate with certainty what should be the price of carbon. There has been until now, and looks like there will always be, great uncertainties about the value of the SCC (John Pezzey, 2018). Indeed, SCC's estimations can be as low as $10\$/tCO_{2,eq}$ or as high as $200\$/tCO_{2,eq}$ currently. Those uncertainties in SCC's value are mainly due to the use of different discount rate values, of different costs, to the difficulties in evaluating the impacts of temperature changes and difficulties in modeling some risks between models.

2.1.3.2 ETS/Cap-and-trade system

In a cap-and-trade system, the government sets an emissions reduction target (also called a cap), in $tCO_{2,eq}$, to be reached for some sectors. The government then delivers the same amount of permits (also called allowances) than the cap value, one permit being equivalent to one $tCO_{2,eq}$. The cap on permits entails a price on permits. Those permits are either auctioned or delivered freely by the government to firms. If auctioned, the government gets money out of it and can re-invest it in social plans, Research & Development (R&D) or environmental actions etc. All firms under by this cap-and-trade system must have, at least, as many permits as the amount of GHG they emit. The integrity of an ETS is checked through Monitoring, Reporting & Verification (MRV) procedures. If a firm does not abide the regulation, it will have to pay a penalty.

Some ETSs also decide to link their scheme to other ETSs (allowances from those ETSs are then mutually recognized as compliance units[1]). They can also recognize certain offset credits as compliance units. Such measures expand the emissions reduction options and the emissions reduction target can be reached at a lower cost. For example, the EU ETS has been linked to the Switzerland ETS since 2017. In addition, since its implementation and up to 2020, the EU ETS allowed international offset credits from the CDM and JI to be used as compliance units to reach its reduction target.

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[1] Compliance unit: A compliance unit is a carbon unit that is recognized as equivalent as its permit by an ETS.

2.1.3.3 ETSs vs carbon tax

Even if most economists do agree on the necessity of carbon pricing, no consensus has been reached on how it should be priced. Some economists, such as Nordhaus or Weitzman, are in favour of using carbon taxes; while others, such as Keohane, are in favor of using cap-and-trade systems. Some other economists favour hybrid mechanisms that combine a carbon tax with an ETS (Goulder and Schein, 2013). This study is not intended to prove that ETSs are superior to carbon taxes, or the other way around. The ETS will be studied here as it is the current way used by the EU ETS to price carbon, the EU ETS being the focus of this study. Two advantages of an ETS can be pointed out: it gives a specific value concerning the future level of emissions; it is a cost-efficient instrument to reach an emissions reduction target (each firm will abate its emissions until its emissions reduction costs equals the permit price).

2.1.3.4 How to correctly define an ETS

According to Partnership for Market Readiness and International Carbon Action Partnership (2016), there are 10 steps the regulator needs to look at to define an ETS:

1. Define which sectors are covered.
2. Define the cap value (the target).
3. Decide how the permits will be allocated (grandfathered or auctioned).
4. Decide whether or not to use (international or domestic) offset credits.
5. Set temporal rules (for banking, borrowing and compliance periods).
6. Define additional policy instruments (such as the ones pointed out in Section 2.3).
7. Make sure concerned firms do comply.
8. Develop communication with stakeholders.
9. Think about linking the ETS with other ETSs.
10. Improve continuously the scheme.

Steps 4 and 6 are the steps this study will focus on in the next Chapters. They will evaluate if defining an offset credits market on a particular ETS model makes sense and if so, what offsets policy instruments implement to efficiently define this offset credits market.

2.1.4 Carbon pricing in the future

With the entering into force of the Paris Agreement by 2021, the future of carbon pricing seems ensured. While it is not an international carbon pricing mechanism in itself, the Paris Agreement lays the ground for the development of such mechanisms through its Article 6 and gives provisions for using international market mechanisms to fulfil the NDCs of the signatory countries. According to the Paris Agreement, Parties have to communicate every five years their Nationally Determined Contribution (NDC). NDCs consist in explaining which measures are taken nationally to reduce GHG emissions. On the 169 NDCs already submitted by Parties, 88 of them do mention the use of carbon pricing to reduce their GHG emissions (World Bank and Ecofys, 2018).

This topic of carbon pricing was particularly visible at the Conference of the Parties (COP) 24 at Katowice in December 2018, during which there were vigorous and numerous debates about carbon pricing. The EU was among the core supporters of carbon pricing and the development of ETSs during this COP (as it was before).

2.2 The EU ETS

In 1997, the Kyoto Protocol set an unprecedented environmental policy measure: for the first time, 37 countries were forced to reduce their emissions according to a target defined by the United Nations Framework Convention on Climate Change (UNFCCC).

Since many countries of the European Union were concerned by the Kyoto Protocol, the European Commission (EC) started in 2000 to think about what policy instruments use to reach its emissions reduction goals. One of them was the implementation of an ETS: the EU ETS was born. The EU ETS Directive was sealed in 2003 and the scheme started in 2005 (European Commission, 2013).

2.2.1 The first three phases: 2005-2020

Until now, the EU ETS has gone through two phases and is currently under the third one.

2.2.1.1 The first phase: 2005-2007

The first phase was a pilot phase to prepare the implementation of the EU ETS. During the phase 1:

- Only CO_2 emissions from power and energy-intensive industries were concerned;
- Permits were freely given to firms;
- Not complying to the scheme cost €40/tCO_2.

During this phase, permits could not be banked[2] by firms. Phase 1 also made possible for the firms to Monitor, Report & Verify (MRV) their emissions for the first time (European Commission, 2013).

2.2.1.2 The second phase: 2008-2012

The second phase started at the same time than the implementation of the Kyoto Protocol, according to which some countries of the EU had emissions reduction target. The main changes compared to phase 1 were:

- In addition to CO_2 emissions, NO_2 emissions were also taken into account for some processes;
- 10% of the permits were sold at auctions;
- Not complying to the scheme cost €100/tCO_2;
- New countries were added to the scheme: Lichtenstein, Iceland and Norway;
- International offset credits from Kyoto Protocol's crediting mechanisms, the CDM and the JI, were recognized as compliance units within the EU ETS.

The cap on emissions was also reduced compared to the first phase (6.5% reduced in comparison to 2005). Nevertheless, with the economic crisis of 2009, emissions reductions were far larger than what was expected. It led to a surplus of permits and offset credits on the EU ETS market, whose effect was mainly a fall in the permits price (European Commission, 2013). A permit was worth around 3.50 €/t$CO_{2,eq}$ in January 2013.

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[2] Banking: it allows offset credits/permits to be saved for future phases.

2.2.1.3 The third phase: 2013-2021

Today, the EU ETS operates in 31 countries in total. More than 11,000 power and emissions-intensive industries are concerned. They represent more than 45% of the EU's Greenhouse Gas emissions (European Commission, 2018a). The key changes compared to the second phase are:

- The emissions reduction target is the same for all EU countries and not specific to each country;
- Perfluorocarbons are taken into account for some industrial processes;
- Back-loading[3] has been introduced to reduce the permits surplus;
- International offset credits are no longer recognized as compliance units within the EU ETS and must be exchanged for EU permits;
- More than half of the permits are auctioned.

Each phase led to improvements but the EU ETS still deals with issues and critics (Branger et al., 2015).

2.2.2 Issues within the EU ETS

Since its implementation, the EU ETS, as every other ETS, has been facing issues. The main ones have been very low permits price and an oversupply of permits/ offset credits on the market (those issues are of course linked).

2.2.2.1 Permits prices

Permits prices have been much lower than anticipated. For example, the EU ETS has seen its permits price drop around 5€/tCO_2 during four years (see the left graph of Figure 2.4). Prices have gotten higher at the end of 2018 but the fact that prices could go so low shows that the market is not functioning well. The right side graph of Figure 2.4 points out what the price of CO_2 should be for the EU to reach its emissions reduction aim by 2050. For example, the permits price should have been around 20 €/tCO_2 in 2015 whereas it cost only 5 €/tCO_2.

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[3] Back-loading: it consists in postponing the auctioning of a certain amount of permits.

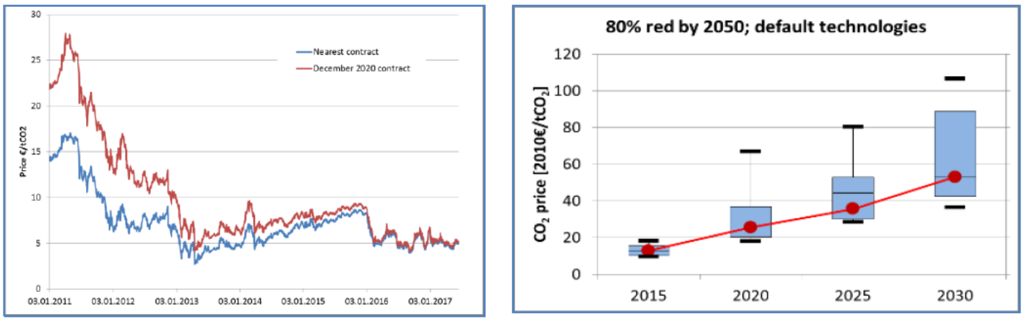

Figure 2.4: Left: permits prices: 2012-2017. Right: what CO_2 price should be so the EU reaches its 2050 target for emissions reduction (Edenhofer et al., 2017)

Having very low permit prices is an issue because it does not give the right signal for investments: investments in high-emitting industries will keep going while investments in low-carbon options will stay low and below what is needed. It will reduce future availability and affordability of low-carbon technologies. Even though the cap will keep declining each year (2.2% for the EU ETS), demand for allowances will stay high (because of past investments in high-emitting technologies). Permits from the Market Stability Reserve (MSR)[4] will therefore be used and permits price will increase. This looks promising but what could actually happen is that the emissions reduction cap could be relaxed if permit prices go too high too rapidly. Investors might be even more reluctant in investing in low-carbon options today considering that the cap might be relaxed (Edenhofer et al., 2017).

Prices are mainly low because of three effects (Edenhofer et al., 2017):
Market myopia: firms under the EU ETS have a short term vision. Permit prices are therefore determined by short term conditions.
Regulatory uncertainty: the regulator decisions need to be reliable and credible to enable long-term investments. For example, the after-2030 EU ETS's cap has not been set yet and remains subject to future political decisions.
State policies: countries can also take specific policy measures to reduce emissions. If the cap is fixed, additional policies to reduce emissions could not lead to additional emission reductions. Due to reduced allowances demand, permit prices might drop and emissions increase.

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[4] See section 2.2.3.1 for more explanation on the MSR.

2.2.2.2 Amount of permits/offset credits

There is currently a surplus of carbon units in the EU ETS: this surplus was close to 2 billion permits at the beginning of phase 3. It decreased to reach 1.78 billion permits in 2015, thanks to back-loading. The carbon units surplus is mainly imputable to the followings (Carbon Pulse, 2017):

- Because of the 2009 crisis, EU ETS firms have produced less and therefore emitted less than first expected. Therefore, the cap set by the EU was easily attainable;
- Banking (which have been allowed since phase 2);
- Some permits have been largely given to some firms in order to avoid carbon leakage[5];
- The fact that international offset credits can be used on the EU ETS adds even more carbon units on the market.

2.2.3 Policy measures taken for the fourth phase: 2021-2030

Several measures have been taken to make the EU ETS stronger and decrease the amount of permits/offset credits on the market. Among others, the target for emissions reduction will be increased from 1.74% currently to 2.2% and the system of free allocation will be revised by 2021 (European Commission, 2018c). Nevertheless, the two biggest changes remain the implementation of a Market Stability Reserve (MSR) and the no longer acceptance of international offset credits.

2.2.3.1 Market Stability Reserve

The EU will start implementing the Market Stability Reserve at the beginning of the fourth period. It is a long-term solution compared to back-loading. Indeed, permits that have not been allocated during the period will be put in the MSR. If permits' availability becomes scarce (or permits price becomes too high (it is not precised how high)), some permits from the MSR will be put back on the market (European Commission, 2018b).

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[5] Carbon leakage: it happens when a firm decides to relocate its activities due to too high costs related to environmental policies.

2.2.3.2 Offset credits market

The EU has a domestic emissions reduction target by 2030: a 40% reduction in its GHG emissions (compared to 1990). To reach this goal, international offset credits from the CDM and JI will not longer be accepted within the EU ETS (European Commission, 2018d). If the EU ETS wants to keep relying on an offset credits market, it will have to define its own domestic offset credits. Those offset credits will have to come from non-EU ETS sectors.

2.3 Other policy measures to solve the EU-ETS issues

Some other policy measures could be used within the EU ETS to solve the issues of units surplus and their low price. Here will be analyzed measures related to steps 4 & 6 of the ten steps defined by Partnership for Market Readiness and International Carbon Action Partnership (2016) in Section 2.1.3.4.

2.3.1 Allowing domestic offset credits

It has been clearly stated by the European Commission (EC) that no more international offset credits will be allowed within the EU ETS by 2021. If the EU ETS wants to keep relying on an offset market, it will have to define a domestic offset credits market. The aim of the Chapter 4 is to evaluate if the EU ETS should or should not develop such a market, using some offsets policy instruments detailed below. Indeed, allowing offsets within ETSs theoretically allows for more flexibility and emissions reduction at lower cost. The amount of domestic offset credits entering the EU ETS should however be limited (using offsets policy instruments) so the EU ETS does not face an oversupply of offset credits.

2.3.1.1 What mechanisms could the EU ETS use to define its domestic offset market?

How could the EU ETS's domestic offset credits market be defined? Different types of offset credits markets do exist. For example, the Clean Development Mechanism (CDM), defined by the Kyoto Protocol, is a project-based mechanism. Each project registered under the CDM must evaluate its BAU emissions and monitor the emissions released during the lifetime of the project. The difference between the BAU and the project's emissions will be converted into offset credits (if the project is acknowledged by the CDM). Even if the EU ETS has been using offset credits from project-based mechanisms, this type of offset credits market is: first, too hard to model (it would have to be modeled project by project); second, not going to be used in the EU ETS after 2021. In this study, it is therefore assumed that the EU ETS's domestic offset market is based on a Sectoral Crediting Mechanism (SCM). A SCM, also called baseline-and-credit mechanism, is defined on one specific sector. It rewards this sector's firms that emit under the sectoral baseline (set at the same value of all firms of the sector). Figure 2.5 shows two emitters from the same sector under a Sectoral Crediting Mechanism.

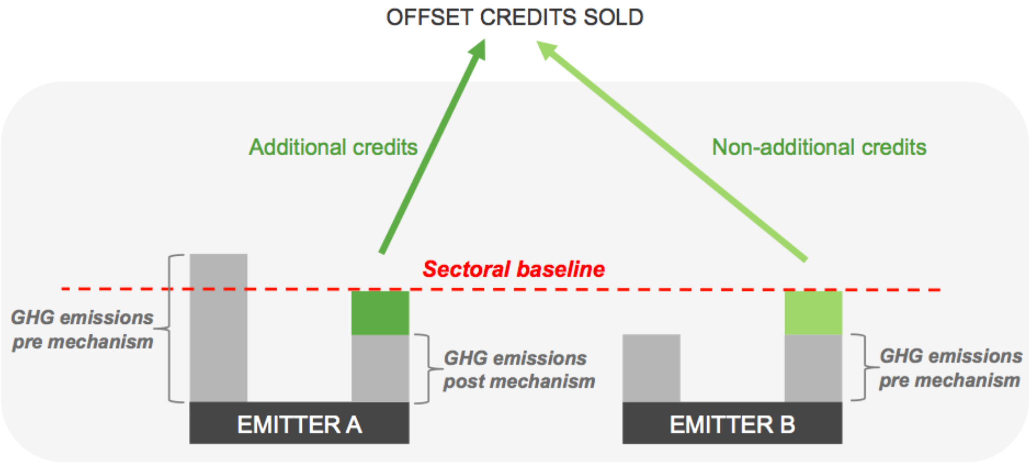

Figure 2.5: Functioning of a Sectoral Crediting Mechanism.

Emitter A emitted above the baseline before the Sectoral Crediting Mechanism's implementation. Emitter A reduced its emissions under the baseline and can therefore sell the difference between the baseline and its current emissions as offset credits. Emitter B emitted under the baseline before the Sectoral Crediting Mechanism's implementation. Without modifying its emissions level, it can also sell an amount of offset credits equivalent to the difference between the baseline and its emissions. Those credits are called "non-additional" offset credits since they do not correspond to real emissions reductions. As the regulator has no information on each firm's level of emissions, it cannot distinguish additional credits from non additional credits. This issue of non-additionality is a current offset credits market issue.

2.3.1.2 Additional offsets policy instruments

Several offsets policy instruments do exist to decrease both the amount of offset credits (to avoid a surplus of offset credits) and the amount of non-additional offset credits put on an ETS. The ones that will be used in this Master thesis stem from BKL and are: setting stricter baseline; using a trade ratio t converting one offset credit into more/less than one permit (one permit is equivalent to one credit divided by a trade ratio t); and finally imposing a limit L on the amount of offset credits that can be sold to ETS' firms. While imposing stricter baselines has an impact on the amount of non-additional offset credits put on the ETS, the other two instruments have an impact on the offset credits price.

During its three first phases, the EU ETS only implemented a limit on the amount of international offset credits that could enter the EU ETS. The objective here is to add two other policy instruments to the limit one and see how their combination impact the EU ETS (by maximizing global welfare).

2.3.2 Introducing a permit price floor

As a response to systematic distortions, some ETSs add price stability to the permits market. For example, putting a price floor is a common feature of North America's ETSs to respond to low permits prices and to tackle the problem of member states having different preferences and wanting to develop national policies. Indeed, theoretically, a cap-and-trade system does not have to be complemented by emissions reduction policies. But usually, domestic emission reduction policies coexist within regional ETSs due to different preferences of member states. To be effective, ETSs should be complemented by a floor price; ie an hybrid system with both elements of emissions trading and tax systems should be put in place (Knopf et al., 2018). Putting a price floor is also a good signal for short-term and mid-term capital decisions and R&D investment decisions; in addition it allows member states to achieve additional emissions reductions (Edenhofer et al., 2017). Implementing such a measure will however not be analysed here because studying the implementation of offsets policy instruments was already a lot of work. It would be interesting though for future work to study the impact of implementing at the same time offsets policy instruments and a permit price floor.

This Chapter presented the importance of implementing a carbon price by highlighting its impact on Sustainable Energy Technologies, such as Renewable Energies for example. It was then explained how to implement carbon pricing, using either a carbon tax or an ETS. The main issues faced by the EU ETS were presented and some measures to deal with them were introduced. The measures that we will focus on are the three offset market policy instruments defined before. Their impact will be studied in the next Chapter, using a simplified model of an ETS allowing the use of offset credits from a SCM. The implementation of the Market Stability Reserve and of a permit price floor will not be taken into account.

Chapter 3

The analytical model

The aim of this chapter is to model an Emissions Trading Scheme (ETS) in which offset credits from a Sectoral Crediting Mechanism (SCM) are allowed. The three offsets policies detailed on Chapter 2 are taken into account. For simplifications, the ETS is comprised of only one sector and the same assumption is made for the SCM. The model is derived from the one of BKL. The model will be applied to the EU ETS case in Chapter 4.

3.1 Designing the ETS

To simplify the model, it is assumed the ETS consists of only one sector (referred to as the "capped sector"). The firms of the capped sector have to detain a permit or an offset credit for each tonne of $CO_{2,eq}$ emitted. The offset credits come from a SCM. The SCM is also assumed to consist of one sector (referred to as the "uncapped sector"). Each sector consists of a unit mass of companies that can abate their emissions. Two periods of time are considered: a pre-intervention period (symbolized by the number 0) and a post-intervention period (symbolized by the number 1). j $= r, u$ designates respectively the capped and the uncapped sector. i designates firm i. Emissions are symbolized with the letter e. A firm i has a Marginal Cost of Abatement (MCA) denoted by the symbol c_j^i, which is assumed to be the same for pre and post carbon market implementation. The values of e_j^i and c_j^i are firm's exclusive information. The regulator only observes density function for GHG emissions and MCA.

3.1.1 ETS: the capped sector

It is assumed that the regulator does not have any firm-specific information. The regulator only knows the mean emissions of the capped sector, $E[e_{r0}]$, and the amount of GHG emitted by the lowest emitter, $\underline{e}_{r0}$. It also knows the maximum, $\overline{c}_{r0}$, and minimum, $\underline{c}_{r0}$, MCA of the capped sector. It is also assumed that the MCA of each capped sector firm is constant. This is a big assumption because usually, the more a firm abates its emissions, the costlier it gets to reduce more emissions. This assumption will therefore be discussed in Chapter 5. Therefore, if a capped firm decides to reduce its emissions, it will reduce them up to zero. This will allow us to analyze an energy sector in Chapter 4 transitioning from high-emitting firms to none-emitting firms (such as Renewable Energies or Nuclear Energies). To simplify calculations, it is assumed that regulated sector's abatement costs are uniformly distributed (see Figure 3.1).

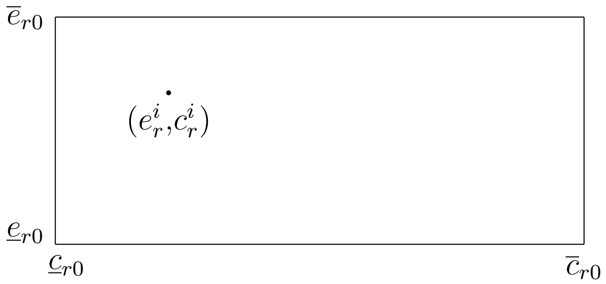

Figure 3.1: Graph presenting the capped sector's model.

Now that the regulator has defined the sector to be capped, it has to choose the amount of permits (A) it will grandfather/auction to capped firms.

It is assumed that offset credits from a particular SCM are allowed on this ETS. The next section explains how this SCM is modeled.

3.1.2 SCM: the uncapped sector

The regulator also allows firms from a SCM to join the program by selling offset credits to capped firms. According to the definition of a SCM, if an uncapped sector's firm emits below the sectoral baseline (the same for each uncapped sector's firms), b, it can sell the difference between its emissions and the baseline as offset credits. The regulator also ignores the level of emissions and MCA of uncapped firms. The regulator only knows the maximum, $\overline{e}_{u0}$, and the minimum, $\underline{e}_{u0}$, level of emissions and the maximum, $\overline{c}_{u0}$, and minimum, $\underline{c}_{u0}$, MCA of the uncapped sector. As for capped firms, MCA are assumed constant for uncapped sector's firms. Therefore, if an uncapped firm decides to reduce its emissions, it will reduce them up to α. Indeed, it is assumed that uncapped firms can sequestrate carbon emissions up to α, with $\alpha < 0$. To simplify calculations, it is assumed that uncapped sector's emissions and MCA are uniformly distributed (see Figure 3.2).

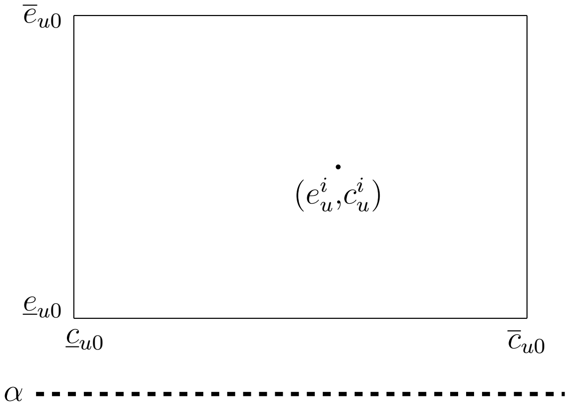

Figure 3.2: Graph presenting the uncapped sector's model.

In order to regulate the amount of offset credits (and with it the amount of non-additional offset credits) on the ETS, three additional offsets policy instruments, as detailed in Chapter 2, are implemented on the SCM: setting a stricter baseline b, using a trade ratio instrument t and defining a limit instrument L. A trade ratio t converts one offset credit into more/less than one permit (one permit is equivalent to one credit divided by the trade ratio t); a limit L sets a limit on the amount of offset credits that can be sold to capped sector's firms.

To efficiently define this offset credits market, the regulator has to optimally combine the three offsets policy instruments so the welfare is maximized.

3.2 Offsets market optimal design

In the case of offset credits not being allowed on the ETS, called the "No offsets" case, the only parameter the regulator can play with to maximize total welfare is the amount of permits A to be put on the market.

If offset credits are allowed on the ETS, the regulator can now play with four parameters to maximize total welfare (welfare of both capped and uncapped sectors): the amount of permits, the baseline value, the trade ratio value and the limit value. BKL showed that, when offset credits are allowed on the ETS, the optimal baseline value is set at the uncapped firms maximum level of emissions, $\underline{e}_{u,0}$, the trade ratio is set at 1, the limit is non-binding and the value of A is way smaller than when offset credits are not allowed on the ETS (see the demonstration in BKL's article). The value of A is reduced to balance the amount of offset credits (additional and non-additional) that enter on the ETS. BKL considers this case, referred as the "First-best" case, as not implementable because of significant distributional effects. Indeed, in BKL's model, capped firms receive their permits freely from the regulator, that is they receive a rent from the regulator. They therefore might oppose seeing their amount of permits diminished compared to the case of offset credits not being allowed on the ETS and make this "First-best" case politically unimplementable: this is called distributional effect. BKL considers that, even if offset credits are allowed on the ETS, the regulator will put on the market the same amount of permits A as for the "No offsets" case. This is referred as the "Second-best" case.

This is what will be considered for the model: A is set at its value when offset credits are not allowed on the ETS and the three offset policy instruments' values are optimized to maximize total welfare.

3.3 Offsets market optimal design under distributional constraints

Since it is considered here that the ETS is under distributional constraints, the value of A is set and the regulator can only maximize the welfare optimizing the parameters b, t and L (as explained in Section 3.2). Total welfare is defined as the benefits minus the costs of implementing the ETS and SCM programs. Society gets benefits (called B) from emissions reductions (called Q) that cost C. Therefore:

$$W = B(Q) - C(Q) \tag{3.1}$$

Capped sector's reduced emissions and associated costs are symbolized by the variables q_r and C_r. Uncapped sector's reduced emissions and associated costs are symbolized by the variables q_u and C_u. So, Q = $q_r + q_u$, C = $C_r + C_u$ and benefits are assumed equal to the multiplication of the Social Cost of Carbon (SCC) by Q:

$$W = B(q_r + q_u) - C_r - C_u = SCC * (q_r + q_u) - C_r - C_u \tag{3.2}$$

It is therefore necessary to calculate the expressions of q_r, q_u, C_r and C_u to evaluate the expression of the welfare and to maximize it. This will be done in the following sections.

3.3.1 Summary of the variables used

Some variables that are to be used in this Section are defined in the Table 3.1:

Table 3.1: Variables used in the model

Variable	Definition
a^i	Permits bought by firm i at price p_a ($tCO_{2,eq}$)
f^i	Offset credits bought by firm i at price p_f ($tCO_{2,eq}$)
q_r	Total capped sector emissions reduction ($tCO_{2,eq}$)
C_r	Total capped sector emissions reduction costs (€)
q_u	Total uncapped sector emissions reduction ($tCO_{2,eq}$)
C_u	Total uncapped sector emissions reduction costs (€)
W	Welfare (€)
E_{UC}	Under-credited emissions[1]($tCO_{2,eq}$)
E_{NA}	Non-additional emissions ($tCO_{2,eq}$)

3.3.2 Capped sector optimization problem

In this section are detailed the calculations of capped firms emissions reduction q_r and associated costs C_r.

3.3.2.1 Maximizing profits

It is assumed here that the regulator auctions the permits to capped firms at a certain price p_a: a^i is the number of auctioned permits bought by firm i. A capped firm i can also buy offset credits from uncapped firms: f^i is the number of offset credits bought by firm i. $e^i_{r,0}$ and e^i_r are respectively the pre and the

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[1] Under-credited emissions: A firm is said to have under-credited emissions reductions when it achieves emissions reductions but cannot convert them into offset credits.

post-policy implementation emissions of firm i. A capped firm's objective is to maximize its profit. Assuming that each firm's production, selling price and costs stay the same between pre- and post-policy implementation (those assumptions will be discussed in Chapter 5), maximizing profit is the same as minimizing policy compliance costs:

$$\begin{aligned} \underset{e^i, a^i, f^i}{\text{minimize}} \quad & p_a a^i + p_f f^i + c_r^i (e_{r0}^i - e_r^i) \\ \text{subject to} \quad & 0 \leq e_r^i \leq e_{r0}^i \\ & e_r^i \leq \frac{f^i}{t} + a^i \\ & 0 \leq \sum_i f^i \leq L \end{aligned} \tag{3.3}$$

The first conditions of the lagrangian of this minimization problem gives (see Annex A-1):

$$p_f = \frac{p_a}{t} - \mu_L \tag{3.4}$$

Depending on the values of t and μ_L, p_f can be either equal, smaller or bigger than p_a. It is interesting to see that the baseline value has no impact on the offset credit price.

3.3.2.2 Total emissions abated, associated costs and permits demand

Firms with MCA lower than p_a will abate their emissions up to zero (region A_1 on Figure 3.3), while firms with MCA higher than p_a will rather buy permits (region A_2 on Figure 3.3). Total emissions abatement and total emissions abatement costs of the regulated sector are therefore (since emissions and MCA are uniformly distributed):

$$q_r = \int_{\underline{c}_r}^{p_a} \int_{\underline{e}_{r0}}^{\bar{e}_{r0}} \frac{e_{r0}}{(\bar{c}_r - \underline{c}_r)} de_{r0} dc_r \tag{3.5}$$

$$C_r = \int_{\underline{c}_r}^{p_a} \int_{\underline{e}_{r0}}^{\bar{e}_{r0}} \frac{e_{r0} * c_r}{(\bar{c}_r - \underline{c}_r)} de_{r0} dc_r \tag{3.6}$$

It is possible to calculate the amount of carbon units (permits or offset credits), D_r, that regulated firms will buy. It corresponds to region A_2 on Figure 3.3:

$$D_r = E[e_{r0}] - q_r \tag{3.7}$$

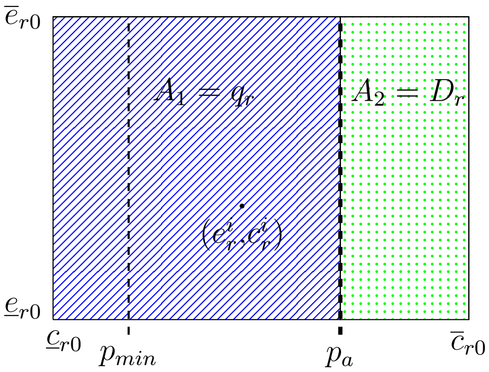

Figure 3.3: Figure representing the capped sector firms reaction to the cap-and-trade program. q_r is equal to the blue patterned area. D_r is equal to the green dotted area.

3.3.3 Uncapped sector optimization problem

In this section are detailed the calculations of uncapped firms emissions reduction q_u and associated costs C_u.

3.3.3.1 Maximizing profits

An uncapped firm i can sell offset credits to capped firms for an amount equal to $b - e_u^i$ (if b > e_u^i) at a price p_f. $e_{u,0}^i$ and e_u^i are respectively the pre- and the post-intervention emissions of firm i. As for regulated firms, uncapped firms want to maximize their profits. Assuming their production stays the same between pre- and post-intervention, with equivalent selling price and production costs (as for the capped sector, those assumptions will be discussed in Chapter 5), maximizing their profit is equivalent in maximizing revenues, R_u^i, from opting in the program:

$$\begin{aligned} \underset{e_u^i}{\text{maximize}} \quad & R_u^i = p_f(b - e_u^i) - c_u^i(e_{u0}^i - e_u^i) \\ \text{subject to} \quad & \alpha \leq e_u^i \leq e_{u0}^i \end{aligned} \tag{3.8}$$

An uncapped firm has two decisions to take: decides whether to opt-in (depending where the baseline b is situated relatively to its e_{u0}^i) and then chooses its level of emissions e_u^i. Uncapped firms will opt-in only if it exists an e_u^i for which $R_u^i > 0$. Then they will choose the "best" e_u^i that maximizes R_u^i. If they do not opt-in, they choose $e_u^i = e_{u0}^i$.

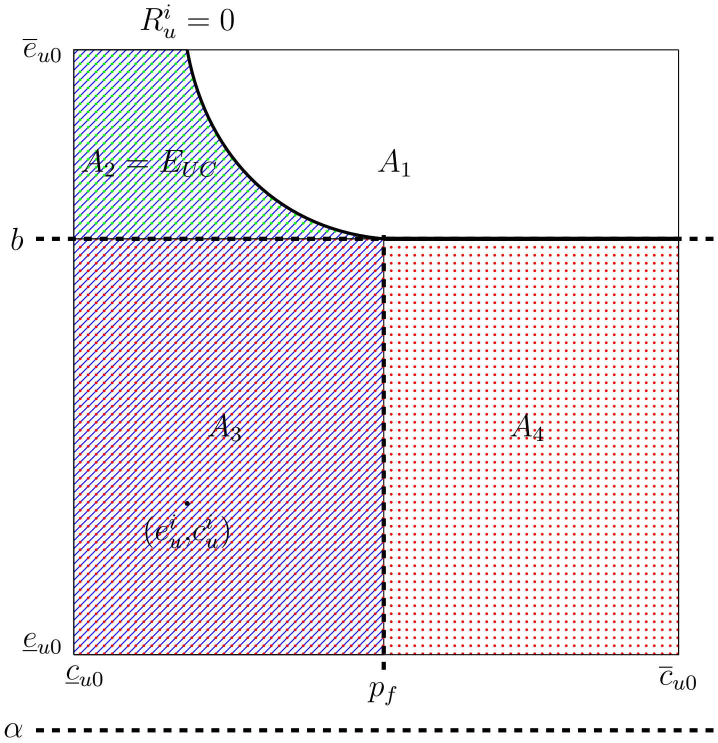

Figure 3.4: Figure representing the uncapped sector firms reaction to the offset program. q_u is equal to the blue patterned area. E_{NA} is equal to the red dotted area. E_{UC} is equal to the green dotted area.

There are two different types of firms opting in:

- Firms for whose $c_u^i < p_f$: R_u^i is positive for any value of e_u^i and is maximized for $e_u^i = \alpha$ (sequestration potential of the unregulated sector);
- Firms for whose $c_u^i > p_f$ and $e_{u0}^i <$ b: R_u^i is positive for any value of e_u^i and is maximized for $e_u^i = e_{u0}^i$.

In summary: if a firm does opt in, it either decreases its emissions to α (and sells (b-α) offset credits), either keeps the same level of emissions as in the pre-intervention case, e_{u0}^i (and sells (b-e_{u0}^i) offset credits). The relationship between e_{u0}^i and c_r^i along $R_u^i = 0$ has to be calculated to evaluate the total abatement of the uncapped sector:

$$p_f(b - e_u^i) - c_u^i(e_{u0}^i - e_r^i) = 0,$$

which gives, e_u^i being equal to α along $R_u^i = 0$:

$$e_{u0}^i = \frac{p_f(b - \alpha) + c_u^i \alpha}{c_u^i} \tag{3.9}$$

On Figure 3.4, firms in the area A_1 do not sell any offsets because $R_u^i < 0$ for every couple (e_u^i,c_u^i) there. Firms in area A_2 do abate their emissions up to α but do not get offset credits for the emissions reduced above b. Those reduced emissions are called under credited emissions reductions. Under credited emissions reductions are emissions reductions that can not be converted into offset credits because they happen above b. Firms in area A_3 do abate their emissions and sell both additional and non-additional offsets. Firms in area A_4 only sell non-additional offsets. Non-additional offsets are offsets that do not correspond to actual abatement: those are sold by firms for which $e_{u0} < b$.

3.3.3.2 Total emissions abatement and costs

According to what was explained above, total emissions abatement and associated costs are (since emissions and MCA are uniformly distributed):

$$q_u = \int_{\underline{c}_u}^{p_f} \int_{\underline{e}_{u0}}^{\widetilde{e}_{u0}} \frac{(e_{u0} - \alpha)}{(\overline{e}_{u0} - \underline{e}_{u0})(\overline{c}_u - \underline{c}_u)} de_{u0} dc_u \tag{3.10}$$

$$C_u = \int_{\underline{c}_u}^{p_f} \int_{\underline{e}_{u0}}^{\widetilde{e}_{u0}} \frac{(e_{u0} - \alpha) * c_u}{(\overline{e}_{u0} - \underline{e}_{u0})(\overline{c}_u - \underline{c}_u)} de_{u0} dc_u, \tag{3.11}$$

where $\widetilde{e}_{u0} = min\{\overline{e}_{u0}, \frac{p_f(b-\alpha)+\alpha c_u}{c_u}\}$ (it corresponds to $R_u^i = 0$).

3.3.3.3 Under-credited and non-additional emissions

As underlined using Figure 3.4, there are both non-additional emissions E_{NA} and under-credited emissions E_{UC} coming out from the SCM. It is due to the fact that the regulator does not have any information on each firm e_{u0}^i and chooses the same baseline for all firms. The expressions of E_{NA} and E_{UC} are the following:

$$E_{NA} = \int_{\underline{c}_u}^{\overline{c}_u} \int_{\underline{e}_{u0}}^{b} \frac{(b - e_{u0})}{(\overline{e}_{u0} - \underline{e}_{u0})(\overline{c}_u - \underline{c}_u)} de_{u0} dc \tag{3.12}$$

$$E_{UC} = \int_{\underline{c}_u}^{p_f} \int_{b}^{\widetilde{e}_{u0}} \frac{(e_{u0} - b)}{(\overline{e}_{u0} - \underline{e}_{u0})(\overline{c}_u - \underline{c}_u)} de_{u0} dc, \tag{3.13}$$

3.3.4 Calculations of p_a and p_f

The price of permits, p_a, is calculated by equalizing the amount of permits, A, and offset credits supplied to the capped sector, f, with the capped sector carbon units demand, D_r. The amount of offset credits f equals:

$$f = q_u - E_{UC} + E_{NA} \tag{3.14}$$

So, equalizing the amount of permits A and offset credits supplied f with the capped sector demand D_r gives:

$$D_r = A + q_u - E_{UC} + E_{NA} \tag{3.15}$$

Solving this equation, using Maple, gives the value of p_a (see Annexes A-4). Now that p_a is known, p_f can be evaluated using Equation 3.4:

$$p_f = \frac{p_a}{t} - \mu_L \tag{3.4}$$

3.3.5 Welfare optimization

The welfare can now be evaluated, since the expressions of q_r, q_u, C_r and C_u are known:

$$W = B(q_r + q_u) - C_r - C_u = SCC * (q_r + q_u) - C_r - C_u \tag{3.2}$$

In the simulations of Chapter 4, the three offset policy instruments will be optimized at the same time to maximize the welfare. Nevertheless, it is also interesting to see how each offsets policy instrument impacts the welfare. This will be done in the next subsection.

3.3.5.1 Impact of the baseline

Firstly, let us examine the impact of changing the baseline value on the supply of offset credits and total emissions. Looking at Figure 3.4, it can be deduced that lowering the baseline of a small variation:

- reduces the supply of non-additional offset credits (since areas A_3 and A_4 are reduced);

- can either increase or decrease the supply of undercredited emissions reductions (on one hand, the area A_2 increases since b is lowered but on the other hand, the area A_2 decreases since the $R_u^i = 0$ slope is more bent);
- reduces the supply of additional offset credits (since area A_3 shrinks).

According to this, a lower baseline increases capped sector emissions abatement since fewer offset credits are issued. The impact on uncapped sector emissions is unclear. The overall effects are resumed in the Table below:

Table 3.2: Impact of a baseline decrease on both sectors' emissions.

	Non-additional offset credits	Additional offset credits	Under-credited emissions reductions	Capped sector emissions	Uncapped sector emissions	Total emissions
Baseline	Reduced	Reduced	Unclear	Reduced	Unclear	Reduced

Secondly, let us look at the impact of an infinitesimal change in the baseline value on the welfare. Capped sector's emissions abatement, q_r, can be written as a function of the capped sector emissions reduction target, T, the non-additional emissions reductions, E_{NA}, the under-credited emissions reductions E_{UC} and the uncapped sector abatement, q_u. T is equal to the BAU emissions of the capped sector minus the amount of permits put on the market. Therefore, the expression of q_r is the following:

$$q_r = T - E_{NA} + E_{UC} - q_u \tag{3.16}$$

Therefore, the expression of the welfare can be rewritten as:

$$W = B(T + E_{UC} - E_{NA}) - C_r(T - E_{NA} + E_{UC} - q_u) - C_u(q_u) \tag{3.17}$$

According to Annex A-1, an infinitesimal variation of the baseline impacts the welfare as follows:

$$\begin{aligned}\frac{\delta W}{\delta b} = & \underbrace{-[B'(.) - p_a]\frac{\delta E_{NA}}{\delta b}}_{dW^{NA}} + \underbrace{[B'(.) - p_a]\frac{\delta E_{EU}}{\delta b}}_{dW^{UC}} + \\ & \underbrace{\int_{\underline{c}_u}^{p_f} \frac{\delta}{\delta b} \int_{\underline{e}_{u0}}^{\widetilde{e}_{u0}} \frac{(p_a - c_u)(e_{u0} - \alpha)}{(\overline{e}_{u0} - \underline{e}_{u0})(\overline{c}_{u0} - \underline{c}_{u0})} de_u dc_u}_{dW^A}\end{aligned} \tag{3.18}$$

BKL details in their article the meaning of the three terms dW^{NA}, dW^{UC} and dW^A, called respectively the Non-additional offset credits effect, the Under-credited emissions reductions and the Additional offset credits effect and their impact on the welfare. Based on Table 3.2, the baseline impacts the marginal welfare as the following:

Table 3.3: Different effects' impact on the marginal welfare relatively to the baseline.

Instrument	Non-additional effect	Additional effect	Under-credited effect	Discounted effect
(a) B'() > p_a				
Baseline	Positive	Negative	Positive	Non-existent
(b) B'() < p_a				
Baseline	Negative	Negative	Negative	Non-existent

3.3.5.2 Impact of the trade ratio

Firstly, let us examine the impact of changing the trade ratio value on the supply of offset credits and total emissions. Looking at Figure 3.4, it can be deduced that setting the trade ratio higher than 1 (meaning one offset credit is converted into less than one permit):

- has no effect on the supply of non-additional offset credits (because those are only related to the baseline setting);
- decreases undercredited emissions reductions (since the offset credits price is lower than the permits price);
- reduces the supply of additional offset credits (same reason as above).

According to this, a trade ratio's increase above 1 decreases capped sector emissions abatement since fewer offset credits are issued. It increases uncapped sector emissions abatement since undercredited emissions reductions are reduced. The overall effects are resumed in the Table below:

Table 3.4: Impact of a trade ratio higher than 1 on both sectors' emissions.

	Non-additional offset credits	Additional offset credits	Under-credited emissions reductions	Capped sector emissions	Uncapped sector emissions	Total emissions
Trade Ratio	No effect	Reduced	Reduced	Reduced	Increased	Unclear

Secondly, let us look at the impact of an infinitesimal change in the trade ratio value on the welfare. Both sectors' emissions abatement, Q, can be written as a function of the capped sector emissions reduction target, T, the non-additional emissions reductions, E_{NA}, the under-credited emissions, reductions E_{UC}, the total amount of offset credits sold to the capped sector, f, and the trade ratio, t. Uncapped sector's emissions abatement, q_u, can be written as a function of the non-additional emissions reductions, E_{NA}, the under-credited emissions, reductions E_{UC}, and the total amount of offset credits sold to the capped sector, f:

$$Q = T - E_{NA} + E_{UC} + (1 - \frac{1}{t})f \tag{3.19}$$

$$q_u = -E_{NA} + E_{UC} + f \tag{3.20}$$

Therefore, the expression of q_r is the following:

$$q_r = Q - q_u = T - \frac{f}{t} \tag{3.21}$$

So the welfare can be rewritten as:

$$W = B(T - E_{NA} + E_{UC} + (1 - \frac{1}{t})f) - C_r(T - \frac{f}{t}) - C_u(q_u) \tag{3.22}$$

According to Annex A-1:

$$\frac{\delta W}{\delta t} = \underbrace{(B'(.) - p_a)f}_{dW^D} + \underbrace{(B'(.) - p_a)\frac{\delta E_{EU}}{\delta t}}_{dW^{UC}} + \underbrace{\int_{\underline{c}_u}^{p_f} \frac{\delta}{\delta t} \int_{\underline{e}_{u0}}^{\widetilde{e}_{u0}} \frac{(p_a - c_u)(e_{u0} - \alpha)}{(\overline{e}_{u0} - \underline{e}_{u0})(\overline{c}_{u0} - \underline{c}_{u0})} de_u dc_u}_{dW^A} \tag{3.23}$$

BKL details in their article the meaning of the dW^D (the Discounted offset credits effect) and the impact of dW^D, dW^{UC} and dW^A on the welfare. Based on the Table 3.4, the trade ratio impacts the marginal welfare as the following:

Table 3.5: Different effects' impact on the marginal welfare relatively to the trade ratio.

Instrument	Non-additional effect	Additional effect	Under-credited effect	Discounted effect
(a) B'() > p_a				
Trade ratio	Non-existent	Negative	Ambiguous	Positive
(b) B'() < p_a				
Trade ratio	Non-existent	Negative	Ambiguous	Negative

3.3.5.3 Impact of the limit

Firstly, let us examine the impact of changing the limit value on the supply of offset credits and total emissions. Looking at Figure 3.4, it can be deduced that lowering the limit, if binding, of a small variation:

- has no effect on the supply of non-additional offset credits (because those are only related to the baseline setting);
- decreases undercredited emissions reductions since the offset credits price is below the permit price when the limit is binding. This price difference discourages uncapped firms from opting-in;
- reduces the supply of additional offset credits (same reason as above).

According to this, a decrease in the limit value increases capped sector emissions abatement since fewer offset credits are issued. It decreases uncapped sector emissions abatement since undercredited emissions reductions are reduced. Compared to the trade ratio instrument, a stricter limit increases overall emissions since it decreases the quantity of undercredited emissions reductions and does not require capped firms to hold more offset credits per unit of emissions. The overall effects are resumed in the Table below:

Table 3.6: Impact of a decrease in the limit value on both sectors' emissions.

	Non-additional offset credits	Additional offset credits	Under-credited emissions reductions	Capped sector emissions	Uncapped sector emissions	Total emissions
Limit	No effect	Reduced	Reduced	Reduced	Increased	Increased

Secondly, let us look at the impact of an infinitesimal change in the limit value on the welfare. The capped sector and uncapped sector's abated emissions have the same expressions as in the Section 3.3.5.1:

$$Q = T - E_{NA} + E_{UC} \tag{3.24}$$

$$q_r = Q - q_u = T - E_{NA} + E_{UC} - q_u \tag{3.25}$$

So the welfare can be rewritten as:

$$W = B(T - E_{NA} + E_{UC}) - C_r(T - E_{NA} + E_{UC} - q_u) - C_u(q_u) \tag{3.26}$$

According to Annex A-1:

$$\frac{\delta W}{\delta L} = \underbrace{(B'(.) - p_a)\frac{\delta E_{EU}}{\delta L}}_{dW^{UC}} + \underbrace{\frac{\delta}{\delta L}\int_{\underline{c}_u}^{p_f}\int_{\underline{e}_{u0}}^{\widetilde{e}_{u0}} \frac{(p_a - c_u)(e_{u0} - \alpha)}{(\overline{e}_{u0} - \underline{e}_{u0})(\overline{c}_{u0} - \underline{c}_{u0})} de_u dc_u}_{dW^A} \tag{3.27}$$

BKL details in their article the impact of dW^{UC} and dW^{A} on the welfare. Based on Table 3.6, the limit impacts the marginal welfare as the following:

Table 3.7: Different effects' impact on the marginal welfare relatively to the limit.

Instrument	Non-additional effect	Additional effect	Under-credited effect	Discounted effect
(a) B'() $> p_a$				
Limit	Non-existent	Negative	Negative	Non-existent
(b) B'() $< p_a$				
Limit	Non-existent	Negative	Positive	Non-existent

3.4 The model applied to the EU ETS

This Chapter modeled an ETS, comprised of only one sector, allowing the use of offset credits from a sector under a SCM. Three offsets policy instruments were implemented to deal with several issues of offset credits market. The aim of the model is to see what combination of the three offsets policy instruments maximizes total welfare. Several assumptions were therefore made to be able to calculate the expression of total welfare.

Next Chapter's aim is to simulate this analytical model with real ETS data to evaluate the values of the three offsets policy instruments that maximize total welfare. The first model's simulation will be based on 2009 Waxman–Markey bill US ETS data. The results will be compared with BKL's ones. The second model's simulation will be based on the EU ETS data. The European Union's sectors are separated in two: the EU ETS sectors (heavy energy-consuming firms (power industrial plants) and airlines running within the EU) and the EU uncapped sectors (mainly transport, buildings, agriculture and waste). In the simulation of next Chapter, only the power sector of the EU ETS will be taken into account. The power sector is an interesting sector to analyze because it will play a future key role in decarbonizing our society and in deploying RE. As for the uncapped sector under the SCM of the model, it will be based on the agricultural sector of the EU.

Chapter 4

The simulations

This chapter starts by detailing the code developed to simulate the analytical model of Chapter 3. Since this analytical model stem from the one of BKL, this Chapter confronts the results achieved with the code developed here (Maple) with the results achieved with BKL's code (Matlab) based on BKL data. Next, our Maple code is run based on data related to the EU ETS. Different cases based on different combinations of the three offset policy instruments are run, the aim being to find the most efficient combination in terms of welfare optimization. This Chapter concludes on a sensibility analysis to study the Social Cost of Carbon (SCC)'s impact on the results.

4.1 The files of the code

The Maple code developed for the simulations is based on the Matlab code developed by BKL but the welfare optimization method might differ (BKL did not actually share how they solved the welfare maximization problem). The simulation code developed consists of three files. A first file called "Common_code.txt" gathers all the functions used for the calculations (the code is detailed in the Annex A-2). For instance, it calculates the capped sector abatement (function called CSA) as a function of the permit's price p_a. A second txt file gathers the data used to calibrate the simulations (see Table 4.3 to see what type of data are included in this file). Finally, a Maple file runs the different cases simulations (see Annex A-3 or A-4 to see how it looks like).

4.2 Checking BKL's results

In this section are presented the results obtained with the Maple code developed in this report, based on the data used by BKL: those data correspond to the 2009 Waxman–Markey bill US cap-and-trade. The capped sector covers coal power plants, petroleum refineries, natural gas refineries, iron and steel production and cement firms. The capped sector firms take equilibrium price as given. The uncapped sector covers agricultural/ forestry sector. The capped sector is allocated a fixed quantity of permits that are equal to capped sector BAU emissions minus a reduction target. BKL assumes there that permits are freely allocated to capped firms: it is as if they were receiving a rent from the regulator, equal to A*p_a.

BKL studied different cases. The "No offsets" case corresponds to the case when no offsets are allowed on the cap-and-trade. The optimal amount of permits, A, to be put on the market and their price, p_a, are calculated maximizing capped sector welfare. In the "First-best" case, the regulator optimally sets the amount of permits, A, and the three offset policy instruments values by maximizing total capped and uncapped sector welfare. BKL showed in their article that in this case, capped firms will see their amount of permits (and therefore their rents) greatly reduced compared to the "No offsets case" and will be more than reluctant to it (see explanations in Section 3.2). This is why "Second-best" cases are developed, which are more politically acceptable to capped firms. In the "Second best" cases, the amount of permits is set to its value in the "No offsets" case. Four different offset policy instruments settings are analysed in the "Second-best" cases to compare how they impact the welfare. In the "Unrestricted" setting, there is no constraints on any of the three policy instruments. The values of the three are optimally set optimizing the welfare. In the "Baseline" setting, a constraint is added on the trade ratio that can not take values under 1. Indeed, the trade ratio's value for the "Unrestricted" setting is equal to 0.67. But a trade ratio lower than 1 might not be politically implementable since it allows capped firms to convert one offset credit into more than one permit. Another instrument lowering emissions should be coupled with a trade ratio lower than 1 (such as lowering the amount of permits, A, or lowering the baseline). This is why the "Baseline" setting adds a constraint on the trade ratio that can only take values higher than 1. In the "Ratio" setting, a constraint is added on the baseline which is set to the uncapped sector emissions mean value to compare the trade ratio and limit instruments. Finally, the "Limit" setting adds two constraints: one on the trade ratio (can not take values under 1) and one on the baseline (set to the uncapped sector emissions mean value). This setting is developed to see if the limit instrument can ever be binding.

4.2.1 Results with our Maple code

The results found with our Maple code are presented in the Tables 4.1 and 4.2. To evaluate the welfare maximum value for each setting of the "Second best" cases, a list of values were set for each offset policy instrument. 60 uniformly distributed range of values between $\underline{e}_{u,0}$ and $\overline{e}_{u,0}$ were defined for the baseline. 60 uniformly distributed range of values between 0 and 2 were defined for the trade ratio. Finally, 60 uniformly distributed range of values between 2% of the permits' amount and 2 $MtCO_{2,eq}$ (this value is way higher than the carbon units need of the capped firms) were defined for the limit. This allowed to calculate 60*60*60 = 216,000 welfare values. The welfare maximum could then be approached and so could the instruments values for the different settings. The same method was used with the EU ETS data.

Table 4.1: Instruments description and composition of capped and uncapped sectors' emissions: data from the 2009 Waxman–Markey bill US cap-and-trade. All values are in Mt$CO2_{eq}$, except the trade ratio.

Outcome	No offsets	First best	Second best			
			Unrestricted	Baseline	Ratio	Limit
Permits	Optimal	Optimal	No-offsets value	No-offsets value	No-offsets value	No-offsets value
Value	4,207	2,793	4,207	4,207	4,207	4,207
Baseline	-	Optimal	Optimal	Optimal	Mean	Mean
Value	-	1,293	-440	-223	365	365
Trade ratio	-	-	Optimal	Restricted	Optimal	Restricted
Value	-	-	0.67	1	1.79	1
Limit	-	-	Optimal	Optimal	Optimal	Optimal
Value	-	-	Non-binding	Non-binding	Non-binding	Non-binding
Capped sector abatement	864	864	680	696	653	450
Uncapped sector abatement	0	486	239	217	171	211
Under-credited abatement	0	0	120	81	24	30
Additional offsets	0	486	116	136	167	181
Non-additional offsets	0	928	4	31	232	232
Offset supply	0	1,414	123	168	379	414
Capped sector emissions	4,207	4,207	4,391	4,374	4,418	4,621
Uncapped sector emissions	365	-121	126	148	194	1,539
Total emissions	4,572	4,086	4,517	4,522	4,613	4,774

The results are very closed to the ones of BKL. They slightly differ because

BKL might have used a different way to solve this maximization problem (they did not detail in their public code how they solved the welfare maximisation problem).

Table 4.2: Welfare and carbon units price for each case. All values are in Mt$CO2_{eq}$, except the permit price (in €/$tCO2_{eq}$) and the rents (€).

Outcome	No offsets	First best	Second best			
			Unrestricted	Baseline	Ratio	Limit
Benefits	21,600	33,750 (+56%)	22,984 (+6%)	22,843 (+6%)	20,582 (-5%)	16,538 (-23%)
Costs	10,800	16,875 (+56%)	8,441 (-22%)	8,389 (-22%)	6,935 (-36%)	4,118 (-62%)
Welfare	10,800	16,875 (+56%)	14,543 (+35%)	14,454 (+34%)	13,648 (+26%)	12,420 (+15%)
Capped sector rents	105,175	69,815	82,789	84,758	79,441	54,829
Permit price	25	25	19.7	20.1	18.9	13.0

4.2.2 Discussion on BKL's results

The discussions of the results in BKL's article is about: the optimal instrument settings for the different cases; the composition of offsets and emissions for each case; the comparison of "Second-best" cases' welfare with the "No offsets" case welfare; finally a paragraph is dedicated to distributional concerns.

4.2.2.1 Discussion on the instrument optimum

According to Table 4.1, the optimal amount of permits found is 4,207 Mt$CO_{2,eq}$ for the "No offsets" case. For the "First-best" case, the baseline value is equal to $\overline{e}_{u0}$ and the amount of permits is lowered at 2,793 Mt$CO_{2,eq}$ to compensate the amount of offset credits (1,414 Mt$CO_{2,eq}$) supplied to the ETS market (2,793 = 4,207 - 1,414). According to BKL, neither the trade ratio, neither the limit are used in this case. The "Second-best" cases correspond to four different policy instruments settings with the amount of permits allocated equal to the optimum of the "No offsets" case. The "Unrestricted" setting combines a low baseline, equal to -447 Mt$CO_{2,eq}$, with a trade ratio lower than 1, equal to 0.67, and a non-binding limit. According to Section 3.3.5, a trade ratio lower than 1 increases the offset credits price. An increased offset credits price results in higher additional offset credits supply and under-credited emissions reductions. The baseline value is lower than for the "Fist-best" case to decrease the non-additional offset credits supply. Lowering the baseline has two effects on the welfare: it increases it since less non-additional offset credits are produced; it decreases it since less uncapped firms can opt-in. This second effect is however balanced by setting the trade ratio lower than 1 (because it increases the offset credits price). According to BKL, the "Unrestricted" setting is unlikely to politically happen because a trade ratio lower than 1 implies that one offset credit can be turned into more than one permit. This is why the "Baseline" setting is analysed: in this setting, the trade ratio is constrained to take only values superior to 1. This setting combines an optimal baseline, equal to -229 Mt$CO_{2,eq}$, with a trade ratio equal to 1 and a non-binding limit. The baseline optimum is a bit higher than in the previous setting because a trade ratio higher than 1 does not support additional offset credits supply. The trade ratio value in this setting is equal to 1 because a trade ratio higher than 1 decreases the offset credits price and therefore fewer uncapped firms opt-in. The "Ratio" setting's aim is to determine which instrument between the ratio and the limit is the most efficient. This is why the baseline is set in this setting at the uncapped firms BAU emissions. The optimal value of the trade ratio is equal to 1.78 and the limit is non-binding: the trade radio is superior to the limit. This was already tangible in Section 3.3.5 where it was shown that, even if both a trade ratio higher than 1 and a binding limit decrease under-credited emissions reductions and additional offset credits supply, the trade ratio has an impact on emissions reduction, while the limit does not. The aim of the last setting, the "Limit" setting, is to figure out if the limit is ever binding. The baseline and the trade ratio are therefore both restricted (the baseline is set to the uncapped sector BAU and the trade ratio to 1). The limit is still non binding. According to those results, it seems legitimate to wonder why limit instruments are used since they do not improve welfare. According to BKL, limit instruments are often used so offset credits are only "supplemental" to capped firms emission reductions.

4.2.2.2 Discussion on offsets and emissions compositions

It is interesting to compare the supply of additional and non-additional offset credits for the different cases. According to Table 4.1, for the "First-best" case, non-additional offset credits are supplied in a huge proportion compared to total offset credits supply: 928 Mt$CO_{2,eq}$ out of 1,414 Mt$CO_{2,eq}$ offset credits are non additional (66%). Indeed, in this case, the baseline is set at its highest value, $\overline{e}_{u0}$, so every capped firm can opt-in. When the baseline is set as high as $\overline{e}_{u0}$, every uncapped firm can earn non-additional offset credits (since each firm's BAU emissions are below each firm's baseline). In the "Unrestricted" setting, non-additional supply is equal to 4 Mt$CO_{2,eq}$. This is because the baseline's optimum value is very low so almost no non-additional offset credits are allocated to uncapped firms. An interesting point to raise is that both sectors' emissions are lower in this setting than for the "No offsets" case. Emissions in the "Unrestricted" setting are lowered by 120 Mt$CO_{2,eq}$ because of the under-credited emissions reductions, which dominates the emissions increase from the supply of non-additional offset credits and from a trade ratio lower than 1. In the "Baseline" setting, since the baseline is higher than for the "Unrestricted" setting, both additional offset credits and non-additional offset credits supplies increase (respectively from 117 to 136 Mt$CO_{2,eq}$ and from 4 to 29 Mt$CO_{2,eq}$) while under-credited emissions reductions decrease from 120 to 81 Mt$CO_{2,eq}$ because the trade ratio can not take values lower than 1 in this case. The "Ratio" and "Limit" settings show higher values for the non-additional offset credits supply: 233 Mt$CO_{2,eq}$. This is due to the fact that neither the trade ratio, neither the limit have an impact on non-additional offset credits supply.

4.2.2.3 Discussion on "Second-best" welfares

Table 4.2 shows among others the welfare values for the different cases and compares them to the "No offsets" case. The "Unrestricted" setting corresponds to a benefits gain of 56% compared to the "No offsets" case. This is due to a larger under-credited emissions reductions compared to non-additional offset credits supply and supplementary emissions reductions because of the trade ratio value (lower than 1). For the "Unrestricted" and "Baseline" settings, the welfare gains are very close, respectively around 35% and 34% compared to the "No offsets case". Adding a constraint on the trade ratio does not therefore impact the welfare gain. For the "Ratio" and "Limit" settings, the welfare gain is lower than for the two other settings: respectively 26% and 15%. There are two relevant things to say about this. First, the welfare gains are lower because neither instruments have an impact on non-additional offset credits supply (this can be seen in the benefits gain which fall by 5% and 23% respectively compared to the "No offsets" case). Second, the "Ratio" setting results in a welfare gain higher compared to the "Limit" setting because the trade ratio being higher than 1 for the "Ratio" setting lowers the emissions (capped firms have to possess 1.78 offset credits for 1 $CO_{2,eq}$). This effect highly balances the fact that a trade ratio higher than 1 dissuades additional offset credits supply.

4.2.2.4 Discussion on "Distributional concerns"

As theoretically explained in Section 3.2, BKL points out the distributional consequences of allowing offset credits in an ETS. In their article, they consider that permits are freely given to firms by the regulator so that capped sector firms receive a "rent" from the regulator equal to A*p_a, A being the amount of permits put on the ETS and p_a the permits price. Allowing offset credits on the ETS decreases this capped sector rents compared to the "No offsets" case. This is proven looking at Table 4.2's calculations. The reduction in rents is the highest for the "First-best" case (falls from 105,175 to 69,815 M€). Even though the "First-best" case achieves the highest welfare, BKL consider that capped firms will refuse the "First-best" case because of this high rents' reduction. This is why "Second-best" cases are studied. The "Unrestricted" setting achieves a high welfare while not decreasing the capped sector rents too much. For the EU ETS case, permits are auctioned to capped firms so it is the regulator that gets a "rent" in that case.

Studying the model simulations results of the 2009 Waxman–Markey bill US cap-and-trade is going to be helpful for the analysis of the EU ETS simulations.

4.3 The EU ETS's results

4.3.1 Parameters' value

For the simulations, several parameters' values are needed. The 2009 Waxman–Markey bill US cap-and-trade parameters values were given in BKL. For the EU ETS simulations, the parameters had to be found. Some of them come from a literature review while others are calculated based on the latter ones.

In the case of the EU ETS, permits' allocation depends on the sector: manufacturing industry for example sees more than half of its permits freely allocated while the energy sector's permits are auctioned. This is why the assumption on permits' distribution was changed compared to BKL model.

4.3.1.1 Parameters from the literature

The Table 4.3 lists all the parameters collected from the literature review. Almost all the values found correspond to year 2015. The BAU emissions of the capped (EU ETS's energy sector) and uncapped (EU's agricultural sector) sectors are the mean emissions of each sector in 2015. The values were found using data from the European Environment Agency (EEA).

Table 4.3: Data used (values are for 2015).

Parameter description	Parameter	Value
Capped sector BAU emissions ($MtCO_{2,eq}$) = energy sector	$E[e_{r0}]$	1333[1]
Uncapped sector BAU emissions ($MtCO_{2,eq}$)	$E[e_{u0}]$	503[1]
Capped sector abatement ($MtCO_{2,eq}$)	A_r	110[2]
Uncapped sector abatement ($MtCO_{2,eq}$)	A_u	252[3]
Social costs of carbon (€$/tCO_{2,eq}$)	SCC	40[4]
Marginal costs of abatement (€$/tCO_{2,eq}$)	MCA	25[5]
Uncapped sector sequestration potential ($MtCO_{2,eq}$)	α	-1556[6]
Percent of non-additional offsets	NA	40%[7]
Reduction target for the EU ETS	T	1.74%[8]

A sector's abatement represents the amount of emissions the sector could reduce at a certain Marginal Cost of Abatement (MCA). The MCA's value is set at 25€$/tCO_{2,eq}$ here. The capped sector's abatement was calculated based on Van den Bergh and Delarue (2015) paper that calculated the Marginal Abatement Cost Curves (MACC) of the energy sector for the following Western European countries: Germany, France, Belgium, the Netherlands, and Luxembourg. Scaling up the MACC to the EU-28 power sector gives the capped sector abatement value at a MCA's value of 25€$/tCO_{2,eq}$. The uncapped sector's abatement value was calculated based on Moran et al.'s paper (2010) which calculated the UK agricultural sector's MACC. Using the ratio between UK and EU-28's agricultural labour units (Eurostat, 2017) gives the uncapped sector abatement value at a MCA's value of 25€$/tCO_{2,eq}$. The SCC is set at 40€$/tCO_{2,eq}$ based on US Environmental Protection Agency calculations (US Environmental Protection Agency, 2017). The uncapped sector has a certain sequestration potential, such as improving efficiencies in ruminants diets, manure management, avoiding CH4 and CO2 from anaerobic digestion, etc (Aertsens et al., 2013). The percent of non-additional offsets, NA, represents the ratio between the amount of non-additional offsets relatively to the total amount of offsets on the market. The value used is the one of the Clean

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[1] (European Environment Agency, 2017)

[2] (Statista, 2017) & (Van den Bergh and Delarue, 2015)

[3] (Bank of England, 2007), (Eurostat, 2017) and (Moran et al., 2010)

[4] (US Environmental Protection Agency, 2017)

[5] (Bento et al., 2015)

[6] (Aertsens et al., 2013)

[7] (Schneider, 2009)

[8] (European Commission, 2019)

Development Mechanism (CDM), the largest carbon offset credits program globally. Finally, the annual reduction target is the one used by the EU ETS for its third period annual, 1,74% (European Commission, 2019).

4.3.1.2 Model calibration

The model is calibrated calculating the other parameters' value based on the literature data. The main literature values used are the BAU emissions, the abatement potential and Marginal Cost of Abatement (MCA) of each sector. Each sector marginal cost's lower bound is set at $0€/tCO_{2,eq}$. Below is detailed how each sector marginal cost's upper bound value is calculated:

$$\overline{c}_{r0} = \frac{MCA * E[e_{r0}]}{A_r} \tag{4.1}$$

$$\overline{c}_{u0} = \frac{MCA * E[e_{u0}]}{A_u} \tag{4.2}$$

$\underline{e}_{u0}$ is evaluated using a function that calculates the percent of non-additional offsets at an offset credits price of $25€/tCO_{2,eq}$ and at a baseline value set at $E[e_{u0}]$ (see function NApct in the Annex A-2). The value found is compared to the 40% value of the literature. Equalizing them gives the value of $\underline{e}_{u0}$. $\overline{e}_{u0}$ is calculated as the following:

$$\overline{e}_{u0} = 2 * E[e_{u0}] - \underline{e}_{u0}$$

It is assumed here, as in BKL, that $\underline{e}_{r0} = \overline{e}_{r0} = E[e_{r0}]$.

The Table 4.4 summarizes the parameters' values used for the model calibration:

Table 4.4: Parameters used for the model calibration.

Parameter description	Parameter	Value
Lower bound of capped sector's MC ($€/tCO_{2,eq}$)	$\underline{c}_{r0}$	0
Upper bound of capped sector's MC ($€/tCO_{2,eq}$)	$\overline{c}_{r0}$	303
Lower bound of uncapped sector's MC ($€/tCO_{2,eq}$)	$\underline{c}_{u0}$	0
Upper bound of uncapped sector's MC ($€/tCO_{2,eq}$)	$\overline{c}_{u0}$	204
Lower bound of uncapped sector's BAU emissions ($MtCO_{2,eq}$)	$\underline{e}_{u0}$	-81
Upper bound of uncapped sector's BAU emissions ($MtCO_{2,eq}$)	$\overline{e}_{u0}$	1,087
Capped sector's BAU emissions ($MtCO_{2,eq}$)	$\overline{e}_{r0}=\underline{e}_{r0}$	1,333

4.3.2 Simulations Analysis

This section gives the results of the simulations. To evaluate and compare the offset policy instruments, the welfare is maximised for different cases and compared. The cases are similar to the ones of the 2009 Waxman–Markey bill US cap-and-trade simulations. The "No offsets" case is the case when no offsets are allowed in the EU ETS. In the "First-best" case, offsets are allowed and the regulator optimally sets the amount of permits allocated and the baseline value. The amount of permits allocated is way smaller compared to the "No offsets" case (to balance the amount of offset credits that enter the market) so this case is politically difficult to implement. In the "Second-best" cases, the amount of permits is therefore set equal to the "No offsets" case and constraints are added on the offset policy instruments to see what instruments prevail upon the others by restraining one at a time. Three settings are analyzed: the "Unrestricted" setting (no constraints on any of the three policy instruments), the "Ratio" setting (one constraint added to the baseline, set at the uncapped sector's mean emissions value) and the "Limit" setting (two constraints added to the trade ratio and the baseline). Finally, the "Alike situation" case tries to model the current offset policy instruments of the EU ETS. During its last phases, the only offset instruments introduced on the EU ETS was the limit instrument. This limit was equal to around 2% of the amount of permits put on the market so it was set here at the second lowest value of the 60 list of values. In The "Alike situation", the baseline is set at the uncapped sector mean emissions value and the trade ratio at 1 (no trade ratio used on the EU ETS).

4.3.2.1 Instruments settings for each case

Table 4.5 gives the results of the different cases. In the "No offsets" case, when no offsets are allowed, the optimal permits' quota is 1,157 $MtCO2_{eq}$. For the "First-best" case, the baseline equals the upper bound of uncapped sector's BAU emissions, $\overline{e}_{u,0}$. The optimal amount of permits is then equal to 170 M$tCO2_{eq}$, a value way lower than the permits amount for the "No offsets" case. The amount of permits is lowered in the "First-best" case to balance the offset credits supplied (987 M$tCO2_{eq}$). In the "Second-best" cases, three different offsets policy instruments settings are run while the permits' amount is set to the "No offsets" case value. The "Unrestricted" setting gives -81$MtCO2_{eq}$ as an optimal value for the baseline. This corresponds to the lowest value it can take, $\underline{e}_{u,0}$. This low baseline is combined with a trade ratio value quite high, equal to 1.53 and a non-binding limit. A trade ratio higher than 1 results in lower offset credits price. A lower offset credits price results in a lower supply of additional offsets and also in lower under-credited emissions reductions. This second effect is balanced by the very low baseline value that increases the under-credited emissions reductions. Such a low baseline compared to the "First-best" case also diminishes the supply of non-additional offsets (from 584 in the "First-best" case to 0 $MtCO2_{eq}$ in the "Unrestricted" setting). Lowering the baseline has two effects on the welfare: it increases it since less non-additional offset credits are produced; it decreases it since less uncapped firms can opt-in. This second effect is however not balanced here, in contrary with the BKL simulation, by setting the trade ratio lower than 1. The "Unrestricted" setting might also be unlikely to happen for political reasons because a baseline set at its lowest value does not encourage any uncapped firms to opt-in. This is why the "Ratio" setting is analysed: in this setting, the baseline's value is set at its mean value $E[e_{u,0}] = 503\ MtCO2_{eq}$. This setting also allows us to compare the trade ratio and limit instruments efficiency, L and t values being set at their optimal values.

Table 4.5: Instruments description and composition of capped and uncapped sectors' emissions: data from the EU ETS. All values, except the trade ratio, are in Mt$CO2_{eq}$.

Outcome	No offsets	First best	Second best			Alike situation
			Unrestricted	Ratio	Limit	
Permits	Optimal	Optimal	No-offsets value	No-offsets value	No-offsets value	No-offsets value
Value	1,157	170	1,157	1,157	1,157	1,157
Baseline	-	Optimal	Optimal	Set	Set	Set
Value	-	1,087	-81	503 (Mean)	503 (Mean)	503 (Mean)
Trade ratio	-	-	Optimal	Optimal	Restricted	Set
Value	-	-	1.53	1.99	1	1
Limit	-	-	Optimal	Optimal	Optimal	Set
Value	-	-	Non-binding	Non-binding	Binding	Non-binding
Capped sector abatement	176	176	116	68	153	10
Uncapped sector abatement	-	403	125	73	0	21
Under-credited abatement	-	0	33	5	0	1
Additional offsets	-	403	91	68	0	20
Non-additional offsets	-	584	0	146	146	146
Offset supply	-	987	91	214	23	166
Capped sector emissions	1,157	1,157	1,217	1,265	1,180	1,323
Uncapped sector emissions	503	100	378	430	503	482
Total emissions	1,660	1,257	1,595	1,695	1,683	1,805

The trade ratio is found to be equal to 1.99 and the limit non-binding. As for BKL data, this result shows that the trade ratio is a superior policy instrument over the limit. Indeed, increasing the trade ratio or decreasing the limit have both the same effect in terms of reducing under-credited emissions and additional offset credits because both instruments decrease the offset credits price. But the trade ratio instrument can have an impact on emissions reductions whereas the limit can not. In the last setting, called "Limit", the baseline b is still set at its mean value and the ratio is now set to 1. The purpose of this setting is to see if the limit can be binding. The result is that the limit is now binding (because it equals the amount of offsets supplied). This differs from the "Limit" setting of BKL data, for which the limit was found non-binding. In the "Alike situation" case, an additional constraint is added on the limit compared to the "Limit" setting. The three offset policy instruments are no longer optimally set but arbitrary fixed by the regulator: the baseline b is still set at its mean value, the ratio is set at 1 and the limit is set at 3.6%*2 M$tCO2_{eq}$ to approach the limit value the EU ETS put on its market during the last phases.

4.3.2.2 Composition of offset credits and capped and uncapped sectors' emissions

Table 4.5 also shows the quantity and composition of offset credits and total emissions for each case. In the "First-best" case, the amount of non-additional offset credits is very high: a bit more than half of offsets supplied are non-additional (584 out of 987 M$tCO_{2,eq}$, i.e 60%). This high amount is due to the optimal value of the baseline, equal to $\overline{e}_{u,0}$. At such a baseline value, any unregulated company can acquire non-additional offsets since each firm pre-implementation emissions are lower than each firm's baseline. Even if capped sector's abatement stays the same between the "No offsets" case and the "First-best" case (176 $MtCO_{2,eq}$), total emissions are quite lower in the "First-best" case than in the "No offsets" case (1,257 M$tCO_{2,eq}$ against 1,660 $MtCO_{2,eq}$). The 403 M$tCO_{2,eq}$ emissions reductions between the two cases are due to uncapped sector emissions reductions. In the "Unrestricted" setting, non-additional emissions are equal to 0 M$tCO_{2,eq}$. It is because the baseline optimal value is equal to $\underline{e}_{u,0}$, the uncapped sector emissions lower bound. So every uncapped firm has its pre-program emissions higher than its baseline. Under-credited emissions reductions now are equal to 33 M$tCO_{2,eq}$. This increase compared to the "First-best" case is due to the lowest value of the baseline (which balances a lower offset credits price due to a trade ratio value higher than 1). Total emissions are also lower than in the "No offsets" case (1,595 against 1,660 M$tCO_{2,eq}$) but higher than in the "First best" case (1,595 against 1,257 M$tCO_{2,eq}$). For the "Ratio" setting, total emissions are now higher than in the "No offsets" case (1,696 M$tCO_{2,eq}$ against 1,660 M$tCO_{2,eq}$). Non-additional emissions are higher than for the "Unrestricted" setting (146 against 0 M$tCO_{2,eq}$) due to the higher baseline value. Under-credited emissions reductions fall from 33 M$tCO_{2,eq}$ to 5 M$tCO_{2,eq}$. This is due to: a higher baseline's value combined with a higher trade ratio value (which lowers offset credits price). For the "Limit" setting, only non-additional offsets are produced by the uncapped sector, equal to 146 M$tCO_{2,eq}$, out of which only 23 M$tCO_{2,eq}$ are supplied to the capped sector since it is equal to the limit optimal value. Since the limit's value is smaller than the amount of non-additional offset credits created, the uncapped sector does not abate its emissions and no under-credited emissions reductions and additional offset credits are produced. The capped sector's abatement increases compared with the "Ratio" setting because very few offset credits are supplied to the ETS and the permits price is quite high (around 34€$/tCO_{2,eq}$): therefore capped firms will rather abate their emissions than buy permits. In the "Alike situation" case, capped sector emissions reductions are the lowest: 10 $MtCO_{2,eq}$. Since the permits price is so low in that setting (2.3€$/tCO_{2,eq}$), firms will rather buy permits/offset credits than abate their emissions. The amount of non-additional emissions reductions is very high (146 non-additional emissions out of 166 $MtCO_{2,eq}$ offsets supplied, i.e 88% of total offset supplied). Compared with the "Limit" setting, the fact that the limit is not binding here allows to put all the non-additional offset credits produced on the ETS. This non-binding limit also allows 20 $MtCO2_{2,eq}$ additional offset credits to enter the ETS. Both sectors total emissions after the policy implementation are the highest of all cases, valuing 1,805 $tMCO_{2,eq}$.

4.3.2.3 Comparison of welfares

This section is dedicated to the analysis of the welfare for the different cases compared with the "No offsets" case (see Table 4.6). For the "No offsets" case, the welfare equals 3,520 M€. Benefits are twice higher than the costs of implementing the EU ETS program. The "First best" case improves the welfare by a +229% gain compared to the "No offsets" case. Both costs and benefits are also +229% greater than the costs and benefits of the "No offsets" case. The "Unrestricted" setting results in a welfare +107% higher than the "No offsets" one and in benefits +37% higher because under-credited emissions reductions (33 $MtCO2_{eq}$) are higher than the supply of non-additional offset credits (0 $MtCO2_{eq}$). This is not as good as the "First best" case but this setting does improve a lot society welfare compared to all the other cases. The "Ratio" setting corresponds to a welfare gain of +38% compared to the

"No offsets" case. This is a low number compared to the +107% gain of the "Unrestricted" setting. This shows that setting a higher baseline has a strong impact on the welfare. What could be interesting for further research is to evaluate what baseline value would give a welfare gain, for example, equal to +70% of the "Unrestricted" setting welfare value. Then, setting a higher baseline than the one of the "Unrestricted" case would not impact so much the welfare. Both the "Ratio" and "Limit" settings' welfare gains are smaller compared to the "Unrestricted" case because the trade ratio and limit instruments do not have any impact on the non-additional offset credits supplied. This impacts the benefits, which are respectively -19% and -13% smaller than for the "No offsets" case. The "Ratio" setting results in a bigger welfare gain than the "Limit" setting thanks to the discounted offsets effect: a trade ratio higher than 1 decreases the emissions because capped firms have to detain more than one offset credit for a unit of emissions. The "Ratio" setting therefore results in a welfare gain compared to the "No offsets" case while the "Limit" setting results in a welfare loss.

Table 4.6: Welfare comparison.

Outcome	No offsets	First best	Second best			Alike situation
			Unrestricted	Ratio	Limit	
Benefits (M€)	7,040	23,168 (+229%)	9,620 (+37%)	5,653 (-19%)	6,114 (-13%)	1,254 (-82%)
Costs (M€)	3,520	11,584 (+229%)	2,319 (-34%)	796 (-77%)	2,656 (-25%)	34 (-99%)
Welfare (M€)	3,520	11,584 (+229%)	7,301 (+107%)	4,856 (+38%)	3,459 (-1%)	1,220 (-65%)

Finally, the "Alike situation" case presents the worst society welfare: -65% welfare loss compared to the "No offsets" welfare. This program is not costly compared to the "No offsets" one (34 against 3,520 M€) because permits and offset credits prices are close to zero (2.3 €/$tCO2_{eq}$): it does not cost a lot to buy permits/offset credits. The program's benefits are also very low compared to the "No offsets" ones (1,254 against 7,040 M€): this is because the sectors do almost not abate their emissions. All "Second-best" settings and the "Alike situation" case's costs are inferior to "No offsets"'s costs because the carbon units prices are lower than in the "No offsets" case and total emissions abatement are lower than, or close to, the "No offsets" case one.

4.3.2.4 Impact of the different policies on the permits' price

This section is dedicated to the analysis of the different settings on the permits and offset credits' price (see Table 4.7).

For the "No offsets" and "First-best" cases, the permits price equals the SCC value, i.e 40 $€/tCO2_{eq}$. For the "Unrestricted" and "Ratio" settings, an offset credit costs less than a permit because the trade ratio is higher than 1. The offset credits price is equal to $0€/tCO2_{eq}$ for the "Limit" setting because the amount of non-additional offsets produced (146 $MtCO2_{eq}$) is higher than the amount of total offsets supplied (21 $MtCO2_{eq}$). This increases the permits price at its highest value compared to the other "Second-best" settings, at $34.7€/tCO2_{eq}$. So, leaving aside that a binding limit results in a welfare loss, a binding limit is interesting in that it increases the price of permits. This is easily understandable as lesser carbon units are available on the ETS so the permits price rises. The "Alike situation" case corresponds to the lowest permits and offset credits price, at 2.3 $€/tCO2_{eq}$ (the prices are the same since the trade ratio equals 1 and the limit is non-binding).

It can be seen on Table 4.5 that the capped sector reduces less emissions for all "Second-best" settings compared to the "First-best" case. It is because the permits and offset credits prices are lower for all "Second-best" settings compared to the "First-best" case so capped firms will rather buy permits/offset credits than decreasing their emissions. An expected result is that the lower the carbon units prices get, the lower the emissions reduction of both sectors are. For instances, the capped sector abatement is of 176 $MtCO2_{eq}$ for the "First-best" case when the permits price is of 40 $€/tCO2_{eq}$. The "Alike situation" case corresponds to the lowest permits and offset credits price, at 2.3 $€/tCO2_{eq}$, and to the lowest capped sector emissions reduction, 21 $MtCO2_{eq}$.

The capped sector here represents the EU ETS energy sector. The assumption that capped sector firms can reduce their emissions up to 0 (while producing the same amount) models emitting power plants turning to Renewable Energies (RE). Therefore, the lowest the emissions reduction of the capped sector, the lowest the REs' deployment. This is also reflected by the permits price: the lower they are, the less the incentive for capped firms to turn to RE.

Table 4.7: Carbon units prices comparison.

Outcome	No offsets	First best	Second best			Alike situation
			Unrestricted	Ratio	Limit	
Permit price (€)	40	40	26.4	15.5	34.7	2.3
Offset credit price (€)	-	40	17.2	7.8	0	2.3

The parameter having the biggest impact on the permits' value is the Social Cost of Carbon (set at 40 €$/tCO2_{eq}$ for the simulations above). It is therefore interesting to make a sensitivity analysis on this parameter.

4.3.3 Sensitivity analysis

The sensitivity analysis will only concern one parameter: the Social Cost of Carbon (SCC) and will be carried out based on the "Unrestricted" setting. It will be studied the impact of the SCC on: the permits' price, offset credits' price, welfare value and total capped and uncapped sectors emissions. The results can be seen in Table 4.8.

Table 4.8: "Unrestricted" case's impacts relatively to SCC's value variations.

SCC (€$/tCO_{2,eq}$)	20	40	60	80	100	120	140	160	180	200
Permits price (€)	13.2	26.4	39.5	52.7	71.8	91.8	111.8	131.8	151.8	171.8
Offset credits price (€)	8.6	17.3	25.9	34.5	35.6	35.6	35.6	35.6	35.6	35.6
Welfare (M€)	1,825	7,301	16,428	29,205	42,598	57,423	74,006	92,350	112,454	134,318
Offset Supply ($MtCO_{2,eq}$)	46	92	138	183	189	189	189	189	189	189
Total emissions ($MtCO_{2,eq}$)	1,716	1,595	1,475	1,355	1,263	1,175	1,087	999	911	823

Surprisingly, a change in the SCC's value does not impact the three offsets instruments optimal value. For all the values taken by the SCC in Table 4.8, the optimal values for the instruments are: b = -81 $MtCO_{2,eq}$, t = 1.53 and L = 189 $MtCO_{2,eq}$. Even if the welfare, the benefits and the costs are impacted by a change in the SCC value, the instruments optimal values stay the same. This is an interesting point for the regulator that implements such offsets policy measures because, even if the SCC value varies over time, the regulator will not have to modify the optimal values of the three offsets instruments.

4.3.3.1 Impact on the permits price

On the Figure 4.1, it can be seen that the higher the SCC value, the higher the permits price value.

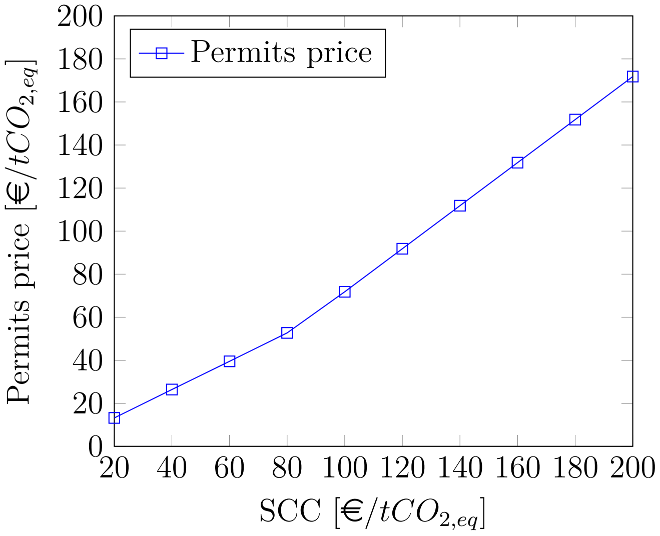

Figure 4.1: SCC variation's impact on the "Unrestricted" setting's permits' price.

This increasing function was expected but not the fact that it would be linear. Indeed, two linear curves are visible on Figure 4.1: a first one for a SCC comprised between 20 €/$tCO_{2,eq}$ and 80 €/$tCO_{2,eq}$ and a second one for a SCC comprised between 80 €/$tCO_{2,eq}$ and 200 €/$tCO_{2,eq}$. The break in the first linear curve is due to to the fact that when the SCC reaches 80 €/$tCO_{2,eq}$, the limit becomes binding (189 $MtCO_{2,eq}$) and the maximum amount of available offsets is reached (and so is the offset credits price), as it can be seen on the Figure 4.2. What is interesting is that when the amount of offset credits entering the ETS is limited by the binding limit, the permits price increase faster relatively to a SCC increase that when the offset credits are not limited. This is easily understandable as, when the offset credits' amount is limited on the ETS, the amount of carbon units on the market diminishes. Therefore, the permits price increases.

4.3.3.2 Impact on the offset credits price

According to equation 3.4, the offset credits price is linked to the permits price. For a SCC comprised between 20 €/$tCO_{2,eq}$ and 80 €/$tCO_{2,eq}$, the limit is non-binding so the limit's Lagrangian parameter, μ_L, equals 0 and the equation becomes (t=1.53 here):

$$p_f = \frac{p_a}{t} \tag{3.4}$$

So the credits price follows the same variation as the permits relatively to a SCC change (see Figures 4.2 and 4.1).

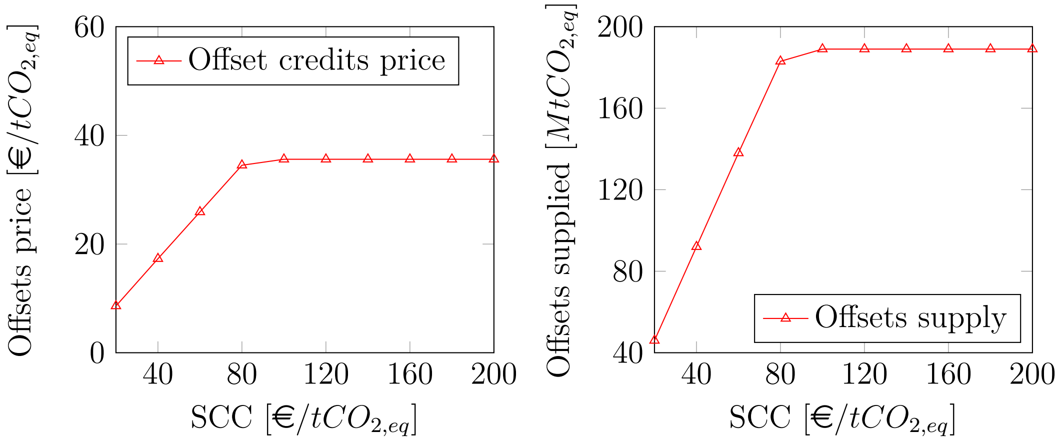

Figure 4.2: SCC variation's impact on on "Unrestricted" setting's offsets' price and offsets supply.

For a SCC comprised between 80 €/$tCO_{2,eq}$ and 200 €/$tCO_{2,eq}$, the limit now becomes binding and the offset credits price is calculated equalizing the amount of offset credits, f, put on the market and the limit value: f = L gives the value of p_f once the limit is binding. The offset credits price does not variate with the SCC value then.

4.3.3.3 Impact on the welfare value

On the Figure 4.3, it can be seen that the welfare increases along a parabolic curve relatively to the SCC value. The higher the SCC gets, the more the welfare function approaches a linear curve. Welfare was expected to increase relatively to the SCC since welfare equals $SCC*Q(.)-C(.)$. Looking into this equation in a simplified way: the term C(.) contains the permits price and offset credits price whereas the term B(.) contains the SCC value. The SCC is always higher than the permits and offset credits prices and the permits and offset credits prices also increase less rapidly than the SCC (see Figures 4.2 (right one) and 4.1). The fact that the welfare increases with the SCC value shows that: the highest is set the SCC value, the highest is the total welfare for society. However, this graph does not give any insight about what could be the "right" value for the SCC: indeed we could be tempted to set the SCC value really high (why not 1,000 €/$tCO_{2,eq}$ since the welfare would be even higher at that price?) but such a value would not be viable for high-emitting firms.

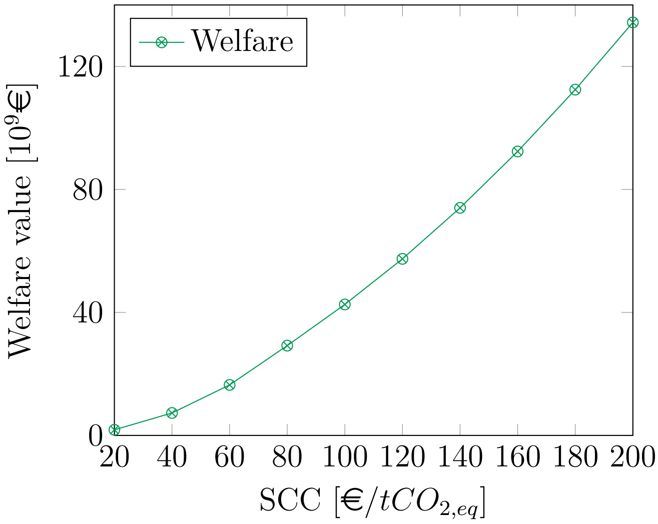

Figure 4.3: SCC variation's impact on "Unrestricted" setting's welfare.

4.3.3.4 Impact on total emissions

It can be seen on the Figure 4.4 that total emissions decrease when the SCC increases.

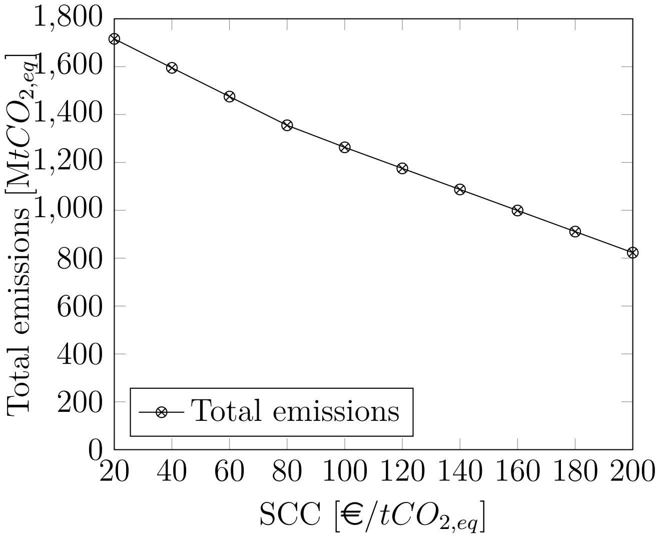

Figure 4.4: SCC variation's impact on "Unrestricted" setting's total emissions.

This decreasing profile is due to the fact that the permits/offset credits prices increase relatively to a SCC increase. The more the permits cost, the more the capped firms will abate their emissions to abide to the program. The more the offset credits cost, the more the uncapped firms will opt-in, sell offset credits and abate their emissions. As the permits price curve relatively to the SCC, this curve presents two linear curve (one before and one after 80 $€/tCO_{2,eq}$). When the SCC is higher than 80 $€/tCO_{2,eq}$, total emissions decrease less rapidly than when the SCC is smaller than 80 $€/tCO_{2,eq}$. Even though the permits price increase rapidly (pushing capped firms to abate their emissions rather than buy permits), no more emissions are abated on the uncapped sector (the offset credits amount equals the limit).

This chapter presented the results of the analytical model simulated with EU ETS data, only taking into account the energy sector of the EU ETS and assuming the domestic offset credits were coming from the agricultural sector (SCM based). The optimized combination of three offset policy instruments were analyzed, based on total welfare optimization. The most efficient way to combine them is to combine a baseline set at a very low value with a trade ratio equal to 1.53 and a non-binding limit ("Unrestricted" setting). Indeed, this instruments combination achieves the highest welfare compared to the other instruments settings. However, this combination results in a permits price equal to $26€/tCO_{2,eq}$, still small compared to what it should be to stay on a 2°C trajectory and to push for RE investments. The sensitivity analysis of the "Unrestricted" setting showed that the higher the SCC value, the higher the permits price value (and the latter increases more rapidly relatively to the SCC when the amount of offset credits are limited). Also, the higher the SCC value is, the more both sectors emissions decrease.

Chapter 5

Conclusion

Thanks to the research done through this report, it is now possible to answer the sub-questions and the main question developed in Chapter 1.

This whole work was done to see how the European Union Emissions Trading System (EU ETS) can improve its carbon offsets market to answer the main two issues it has been confronted with: an oversupply of carbon units and very low permits prices (the first issue of course impacts the second one). Why is it important for the EU ETS to have a high permits price? Because it reflects the current carbon price and it sends the signal to investing companies that it is time to switch from high-emitting technologies to Sustainable Energy Technologies (SET) ones and in particular from fossil fuels to Renewable Energies (RE). This shift is urgent to tackle climate change and change the trend rapidly. Different policy measures could be implemented on the EU ETS to solve the two issues mentioned above: those measures can be permits-market-based or offsets-market-based. For example, a price-floor could be implemented on the EU ETS so the permits price would not go lower than a certain value (permits-market-based measure). A trade ratio converting an offset credit into more/or less than a permit could be implemented on the offsets market of the EU ETS to impact the amount of offset credits entering the EU ETS (offsets-market-based measure).

The EU ETS will implement new measures to answer its issues for its 4th period, stating in 2021. The main ones are: the implementation of a Market Stability Reserve (MSR) (permits-market-based measure) and a domestic reduction objective after 2021. This means that no more offset credits coming from outside the EU will be allowed on the EU ETS market by 2021 (offsets-market-based measure). This report's aim was to assess if the EU ETS, in its current form, should still use offset credits and therefore if it should develop a domestic carbon offsets market after 2021. A model was therefore developed to model the EU ETS (only taking into account the energy sector of the EU ETS) and to model what could be its domestic carbon offsets market. This domestic offsets market was assumed to be Sectoral Crediting Mechanism (SCM)-based. A SCM is a baseline-and-credit scheme which sets the same baseline for each firm of a specific sector. Firms that choose to opt-in can sell offset credits to capped firms by decreasing their emissions below the baseline. Three offsets policy measures, stemming from Bento et al. (2015) article, were analyzed to see if they impacted the EU ETS's issues mentioned above. The three measures are: setting stricter baselines, using a trade ratio turning an offset credit into more/less than one permit and putting a limit on the amount of offset credits allowed on the EU ETS. Those instruments have an impact on the amount of offsets supplied, the nature of the offsets supplied and, therefore, on the permits price. To find how to combine the three instruments in the most effective manner (in terms of society welfare maximisation), an analytical model was developed based on Bento et al. one. This model was simulated with current EU ETS data, only taking into account the energy sector of the EU ETS and assuming the domestic offset credits were coming from the agricultural sector (SCM based). It was found that the most efficient way to combine the three offsets instruments was to combine a baseline set at a very low value with a trade ratio equal to 1.53 and a non-binding limit. This setting is called "Unrestricted". Indeed, this instruments combination allows to achieve the highest welfare compared to the other instruments settings. It results though in a permits price equal to 26 $€/tCO_{2,eq}$, still small compared to what it should be to stay on a 2°C trajectory. Setting a low baseline has two effects on the welfare: it increases it since less non-additional offset credits can be sold on the EU ETS; it decreases it since less uncapped firms can opt-in (the first effect exceeds the second one). However, setting such a low baseline might be politically uninteresting since it does not encourage any uncapped firm to opt-in. This is why an other setting was analyzed, with a constraint added on the baseline, set at the mean value of the uncapped sector's emissions (the other two instruments being optimally set). This instruments combination results in a much lower welfare value. It could be interesting to analyze which baseline constraint would allow to reach a welfare value for example equal to 70 % of the first combination.

Those simulations show two things:

- First, the EU ETS should still consider implementing an offsets market by 2021. This is shown comparing the "Unrestricted" setting results with the "No offsets" case results. It should however be careful on limiting the amount (and the quality) of carbon offset credits entering its carbon market by implementing offsets policy measures.

- Second, if so, the EU ETS should rethink what offsets policy instruments to use. Indeed, the "Unrestricted" setting achieves a better outcome than the "Alike situation" case, where the three offsets policy instruments are set to approach at best the current offsets policy measures of the EU ETS. Therefore, in this setting, the trade ratio equals 1 (since there is none on the current carbon offsets market of the EU ETS), the limit is set at a value close to the one of the EU ETS and the baseline is set at the BAU uncapped sector's emissions. The baseline does not really reflect the carbon offsets market of the EU ETS since the EU ETS is currently relying on project-based mechanisms and not on SCM ones. If we broaden the results of this model (based on a SCM) to the carbon offsets market of the EU ETS (project-based), the EU ETS should not use a limit instrument but rather use a trade ratio instrument (and a baseline if it decides to switch to a SCM offsets market).

To reach those conclusions, a lot of simplifications were made for the model.

- First, it was assumed the EU ETS would implement a domestic Sectoral Crediting Mechanism. Implementing an other crediting mechanism would result in a different amount of offset credits. Nevertheless, the offsets policy measures developed here could still be used on any other crediting mechanism and their impact on offset credits composition would be the same. The results would therefore look alike if another crediting mechanism with the same offsets policy instruments were analyzed.
- Second, some assumptions on firms' emissions characteristics were made. It was assumed that the Marginal Cost of Abatement (MCA)'s values were fixed, that each firm's production, selling price and costs stayed the same between pre- and post-policy implementation. In practice, MCAs are not fixed since the more emissions a firm abates, the more costly it gets to reduce its emissions. Also, if a firm reduces its emissions, it either impacts its production (maybe it produced less to reduce its emissions), either impacts its selling price (maybe it changed of technology to reduce its emissions so the costs and selling prices would change). Those assumptions were made to simplify the model. They impact a lot the post-implementation capped sector's emissions since firms will not reduce of the same amount their emissions under different assumptions. The amount of carbon units required by the capped firms to cover their

emissions will therefore differ. The optimal combination of offsets policy instruments for the "Unrestricted" setting might also differ from our results but the outcome will still be that implementing a carbon offsets market outperforms, from a welfare point of view, the "No Offsets" case.

- Third, no banking was considered here since only one period of time was taken into account. Banking can have a huge impact on the carbon units oversupply. Banking could be implemented in a more complex version of this model. The regulator could balance it by putting less permits on the market.
- Fourth, the value of the Social Cost of Carbon (SCC) was set at 40 $€/tCO_{2,eq}$ for the simulations. This value was taken from US Environmental Protection Agency (2017) but the "right" value of the SCC (if there is one!) is still under debate. However, the sensitivity analysis showed that the value of the SCC does not impact the most efficient combination of the three offsets policy instruments. The results of the "Unrestricted" setting would therefore still be valid with another value of the SCC.
- Finally, the method of solving the welfare optimization problem could be improved (even if the one used here was already performing). Indeed, only 60 values per offsets instruments were used to approach the welfare maximum. The results would have been more precise with more values but the simulations already took 7 hours to run. If each set of values were to be multiplied by 2, it would multiply the time of running per 8 so the simulations would take 56 hours to run. This optimization method does not impact the results since it gave the same results than BKL (based on BKL data).

Implementing an offset credits market is not the only answer to the EU ETS' low permits price. A first measure would be to stop over-allocating permits as an answer to potential carbon leakage. Another measure mentioned in Chapter 2 (but not analyzed in the model) that could solve this issue would be the implementation of a permit price floor. According to Edenhofer et al. (2017) and Knopf et al. (2018), a permit price floor would overcome the low permit price issue and would also send a good signal for short and miterm capital decisions. However, this measure might be politically tricky to implement (viewed as a tax by firms) and brings us back to the question of assessing the right value to carbon. ETSs could also be combined with states complementary policies. Those complementary policies could: first, prevent failures of future EU ETS reforms; and second, answer some market failures (the EU ETS can not address all the relevant market failures). For example, policies encouraging the development of Renewable Energies (RE), such as premium tariffs, could be implemented if the EU ETS' permits price fails to send the right signal.

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Appendices

A-1 Analytical model

Appendix 1

The Lagrangian of this minimization problem is, μ_λ, μ_{e1}, μ_{e2}, μ_a, μ_f and μ_L being lagrangian multipliers:

$$\Lambda(e_r^i, a^i, f^i) = p_a a^i + p_f f^i + c_r^i(e_{r0}^i - e_r^i) + \mu_\lambda(\frac{f^i}{t} + a^i + a_0^i - e_r^i) - \\ \mu_{e1} e_r^i - \mu_{e2}(e_{r0}^i - e_r^i) - \mu_a(a^i + a_0^i) - \mu_f f^i - \mu_L(L - f^i) \quad (1)$$

The first order conditions give:

$$p_a + \mu_\lambda - \mu_a = 0 \quad (2)$$

$$p_f + \frac{\mu_\lambda}{t} - \mu_f + \mu_L = 0 \quad (3)$$

If it is assumed that permits are exchanged and offsets bought, then the limit on μ_a and μ_f is not binding and both μ_a and μ_f equal zero. So we get:

$$p_a + \mu_\lambda = 0 \quad (4)$$

$$p_f + \frac{\mu_\lambda}{t} + \mu_L = 0, \quad (5)$$

ie:

$$p_f = \frac{p_a}{t} - \mu_L \quad (6)$$

Appendix 2

The welfare derivation relatively to the baseline gives:

$$\frac{\delta W}{\delta b} = [B'(.) - C_r'(.)]\frac{\delta E_{EU}}{\delta b} - [B'(.) - C_r'(.)]\frac{\delta E_{NA}}{\delta b} + C_r'\frac{\delta q_u}{\delta b} - \frac{\delta C_u}{\delta b} \quad (7)$$

The derivation of C_r relatively to q_r gives:

$$\frac{dC_r}{dq_r} = \int_{\underline{e}_{r0}}^{\overline{e}_{r0}} \frac{dp_a}{dq_r} p_a \frac{e}{(\overline{e}_{r0} - \underline{e}_{r0})} de \quad (8)$$

$$\frac{dq_r}{dp_a} = \int_{\underline{e}_{r0}}^{\overline{e}_{r0}} \frac{e}{(\overline{e}_{r0} - \underline{e}_{r0})} de = 1 \quad (9)$$

So:

$$\frac{dC_r}{dq_r} = p_a \int_{\underline{e}_{r0}}^{\overline{e}_{r0}} \frac{e}{(\overline{e}_{r0} - \underline{e}_{r0})} de = p_a \tag{10}$$

Therefore:

$$\begin{aligned}\frac{\delta W}{\delta b} = \underbrace{-[B'(.) - p_a]\frac{\delta E_{NA}}{\delta b}}_{dW^{NA}} + \underbrace{[B'(.) - p_a]\frac{\delta E_{EU}}{\delta b}}_{dW^{UC}} + \\ \underbrace{\int_{\underline{c}_u}^{p_f} \frac{\delta}{\delta b} \int_{\underline{e}_{u0}}^{\widetilde{e}_{u0}} \frac{(p_a - c_u)(e_{u0} - \alpha)}{(\overline{e}_{u0} - \underline{e}_{u0})(\overline{c}_{u0} - \underline{c}_{u0})} de_u dc_u}_{dW^{A}}\end{aligned} \tag{11}$$

Appendix 3

The welfare derivation relatively to the trade ratio gives, since E_{NA} does not depend on t:

$$\frac{\delta W}{\delta t} = B'(.)\frac{\delta E_{EU}}{\delta t} + B'(.)\frac{\delta}{\delta t}[(1 - \frac{1}{t})f] + C_r'(.)\frac{\delta}{\delta t}(\frac{f}{t}) - \frac{\delta C_u}{\delta t} \tag{12}$$

The derivation of f relatively to t gives:

$$\frac{\delta f}{\delta t} = \frac{\delta q_u}{\delta t} - \frac{\delta E_{UC}}{\delta t} \tag{13}$$

So:

$$\begin{aligned}\frac{\delta W}{\delta t} = B'(.)\frac{\delta E_{EU}}{\delta t} + B'(.)[(1 - \frac{1}{t})\frac{\delta q_u}{\delta t} - (1 - \frac{1}{t})\frac{\delta E_{UC}}{\delta t} + \frac{f}{t^2})] + \\ C_r'(.)[-\frac{\delta E_{UC}}{\delta t}\frac{1}{t} + \frac{\delta q_u}{\delta t}\frac{1}{t} - \frac{f}{t^2}] - \frac{\delta C_u}{\delta t}\end{aligned} \tag{14}$$

We evaluate this expression in t=1 since it is the first best (so optimal) value and see how a small change around 1 is impacting this equation. The equation above is evaluated for t=1:

$$\frac{\delta W}{\delta t} = B'(.)\frac{\delta E_{EU}}{\delta t} + B'(.)f + C_r'(.)[-\frac{\delta E_{UC}}{\delta t} + \frac{\delta q_u}{\delta t} - f] - \frac{\delta C_u}{\delta t} \tag{15}$$

Finally, since we showed before that $C_r'(.) = p_a$:

$$\frac{\delta W}{\delta t} = \underbrace{(B'(.) - p_a)f}_{dW^D} + \underbrace{(B'(.) - p_a)\frac{\delta E_{EU}}{\delta t}}_{dW^{UC}} + \underbrace{\int_{\underline{c}_u}^{p_f} \frac{\delta}{\delta t} \int_{\underline{e}_{u0}}^{\widetilde{e}_{u0}} \frac{(p_a - c_u)(e_{u0} - \alpha)}{(\overline{e}_{u0} - \underline{e}_{u0})(\overline{c}_{u0} - \underline{c}_{u0})} de_u dc_u}_{dW^A} \tag{16}$$

Appendix 4

The welfare derivation relatively to the limit gives, since E_{NA} does not depend on L:

$$\frac{\delta W}{\delta L} = B'(.)\frac{\delta E_{EU}}{\delta L} - C_r'(.)\frac{\delta E_{EU}}{\delta L} + C_r'(.)\frac{\delta q_u}{\delta L} - \frac{\delta C_u}{\delta L} \tag{17}$$

Since $C_r'(.) = p_a$, the above equation becomes:

$$\frac{\delta W}{\delta L} = (B'(.) - p_a)\frac{\delta E_{EU}}{\delta L} + p_a\frac{\delta q_u}{\delta L} - \frac{\delta C_u}{\delta L} \tag{18}$$

And therefore:

$$\frac{\delta W}{\delta L} = \underbrace{(B'(.) - p_a)\frac{\delta E_{EU}}{\delta L}}_{dW^{UC}} + \underbrace{\frac{\delta}{\delta L}\int_{\underline{c}_u}^{p_f} \int_{\underline{e}_{u0}}^{\widetilde{e}_{u0}} \frac{(p_a - c_u)(e_{u0} - \alpha)}{(\overline{e}_{u0} - \underline{e}_{u0})(\overline{c}_{u0} - \underline{c}_{u0})} de_u dc_u}_{dW^A} \tag{19}$$

A-2 Common code

```
CSA := proc(p)
global cmin_r, cmax_r, emean_r:
description "capped sector abatement, q_r" :
emean_r*(p - cmin_r)/(cmax_r - cmin_r)
end proc :

CSAC := proc(p)
global cmin_r, cmax_r, emean_r:
description "capped sector abatement costs, C_r":
# Int(c*emean_r/(cmax_r - cmin_r), c = cmin_r..p)
emean_r*(p - cmin_r)*(p + cmin_r)/2/(cmax_r - cmin_r)
end proc :
```

```
Demand := proc(p)
global cmin_r, cmax_r, emean_r:
description "demand for permits/offsets from the
   uncapped sector = e_mean_r − CSA(p)":
emean_r*(cmax_r − p)/(cmax_r − cmin_r)
end proc :

Welfare := proc(Q,C)
global SCC :
description "Welfare calculation", "Q : total abatement
   ", "C : total costs":
SCC*Q − C
end proc :

Rents := proc(p,A)
description "Rents calculation", "p : permit price":
A*p
end proc :

Excess_nooffsets := proc(p,A)
description "difference between permit allocation and
   demand for permits/offsets",
            "p : permit price":
A − Demand(p)
end proc :

Totalabatement_nooffsets := CSA :

Totalabatementcosts_nooffsets := CSAC :

USA_fullinformation := proc(p)
global cmin_u, cmax_u, emean_u, alpha:
description "Uncapped sector abatement, q_u",
"Int(Int((e−alpha)/2/(emean_u − emin_u )/(cmax_u −
   cmin_u), e = emin_u..2*emean_u−emin_u), c = cmin_u..
   p)":
(emean_u − alpha)*(p − cmin_u)/(cmax_u − cmin_u)
end proc :

USAC_fullinformation := proc(p)
global cmin_u, cmax_u, emean_u, alpha:
```

```
description "uncapped sector abatement costs, C_u",
"Int(Int(c*(e-alpha)/2/(emean_u-emin_u)/(cmax_u-cmin_u)
   , e = emin_u..2*emean_u-emin_u), c = cmin_u..p)":
(emean_u - alpha)*(p - cmin_u)*(p + cmin_u)/2/(cmax_u -
    cmin_u)
# = USA_fullinformation(p)*(p + cmin_u)/2
end proc :

Offsetssupply_fullinformation := USA_fullinformation :

Excess_fullinformation := proc(p,A)
description "difference between permit allocation and
   demand for permits/offsets",
            "p : permit price":
A + Offsetssupply_fullinformation(p) - Demand(p)
# = Excess_nooffsets(p,A) + USA_fullinformation(p)
end proc :

Totalabatement_fullinformation := CSA +
   USA_fullinformation :

Totalabatementcosts_fullinformation := CSAC +
   USAC_fullinformation :

USA_noinformation := proc(p_f)
local ctilde_min :
global cmin_u, cmax_u, emean_u, emin_u, alpha, b :
description "uncapped sector abatement, q_u",
            "p_f : offsets price", "see calculations in
                 _No_information":
ctilde_min := p_f*(b - alpha)/(2*emean_u - emin_u -
   alpha) :
if ctilde_min < cmin_u then
((emin_u-alpha)^2*cmin_u - p_f*((b-alpha)^2 + (emin_u-
   alpha)^2) + p_f^2*(b-alpha)^2/cmin_u)/4/(emean_u-
   emin_u)/(cmax_u-cmin_u)
# Int(Int((e - alpha)/2/(emean_u - emin_u)/(cmax_u -
   cmin_u), e = emin_u..alpha+p_f*(b-alpha)/c), c =
   cmin_u..p_f)
else
(2*p_f*(b-alpha)*(2*emean_u-emin_u-alpha)-4*cmin_u*(
   emean_u-emin_u)*(emean_u-alpha)-p_f*(b-alpha)^2-p_f
```

```
    *(emin_u-alpha)^2)/4/(emean_u-emin_u)/(cmax_u-cmin_u
    )
# Int(Int((e-alpha)/2/(emean_u - emin_u)/(cmax_u -
    cmin_u), e = emin_u..2*emean_u-emin_u), c = cmin_u..
    ctilde_min) + Int(Int((e-alpha)/2/(emean_u - emin_u)
    /(cmax_u - cmin_u), e = emin_u..alpha+p_f*(b-alpha)/
    c), c = ctilde_min..p_f)
fi end proc:

USAC_noinformation := proc(p_f)
local ctilde_min :
global cmin_u, cmax_u, emean_u, emin_u, alpha, b :
description "uncapped sector abatement costs, C_u",
                "p_f : offsets price", "see calculations in
                     _No_information":
ctilde_min := p_f*(b - alpha)/(2*emean_u - emin_u -
    alpha) :
if ctilde_min < cmin_u then
(2*p_f^2*(b-alpha)^2*ln(p_f/cmin_u)-(p_f-cmin_u)*(p_f+
    cmin_u)*(emin_u-alpha)^2)/8/(emean_u-emin_u)/(cmax_u
    -cmin_u)
# Int(Int(c*(e-alpha)/(2*(emean_u - emin_u))/(cmax_u -
    cmin_u), e = emin_u..alpha+p_f*(b-alpha)/c), c =
    cmin_u..p_f)
else
(2*p_f^2*(b-alpha)^2*ln((2*emean_u-emin_u-alpha)/(b-
    alpha))+(b-emin_u)*(b-2*alpha+emin_u)*p_f^2-4*cmin_u
    ^2*(emean_u-emin_u)*(emean_u-alpha))/8/(emean_u-
    emin_u)/(cmax_u-cmin_u)
# Int(Int(c*(e-alpha)/(2*(emean_u - emin_u))/(cmax_u -
    cmin_u), e = emin_u..2*emean_u-emin_u), c = cmin_u..
    ctilde_min) + Int(Int(c*(e-alpha)/(2*(emean_u -
    emin_u))/(cmax_u - cmin_u), e = emin_u..alpha+p_f*(b
    -alpha)/c), c = ctilde_min..p_f)
fi end proc:

UC_noinformation := proc(p_f)
local ctilde_min :
global cmin_u, cmax_u, emean_u, emin_u, alpha, b :
description "Undercredited emissions, E_UC",
                "p_f : offsets price", "see calculations in
                     _No_information":
```

```
ctilde_min := p_f*(b - alpha)/(2*emean_u - emin_u -
    alpha) :
if ctilde_min < cmin_u then
(b-alpha)^2*(p_f^2/cmin_u-2*p_f*ln(p_f/cmin_u)-cmin_u)
    /4/(emean_u-emin_u)/(cmax_u-cmin_u)
# Int(Int((e-b)/2/(emean_u - emin_u)/(cmax_u - cmin_u),
     e = b..alpha+p_f*(b-alpha)/c), c = cmin_u..p_f)
else
((2*emean_u-emin_u-b)*(2*p_f*(b-alpha)-cmin_u*(2*
    emean_u-emin_u-b))+2*p_f*(b-alpha)^2*ln((b-alpha)
    /(2*emean_u-emin_u-alpha)))/4/(emean_u-emin_u)/(
    cmax_u-cmin_u)
# Int(Int((e-b)/(2*(emean_u - emin_u))/(cmax_u - cmin_u
    ), e = b..2*emean_u-emin_u), c = cmin_u..ctilde_min)
     + Int(Int((e-b)/(2*(emean_u - emin_u))/(cmax_u -
    cmin_u), e = b..alpha+p_f*(b-alpha)/c), c =
    ctilde_min..p_f)
fi end proc :

USA_minus_UC_noinformation := proc(p_f)
local ctilde_min :
global cmin_u, cmax_u, emean_u, emin_u, alpha, b :
ctilde_min := p_f*(b - alpha)/(2*emean_u - emin_u -
    alpha) :
if ctilde_min < cmin_u then
(2*p_f*(b-alpha)^2*ln(p_f/cmin_u) - ((b-alpha)^2+(
    emin_u-alpha)^2)*(p_f-cmin_u))/4/(emean_u-emin_u)/(
    cmax_u-cmin_u)
else
(((b-emin_u)^2-4*(b-alpha)*(emean_u-emin_u))*cmin_u - (
    b-emin_u)*(2*alpha-b-emin_u)*p_f - 2*p_f*(b-alpha)
    ^2*ln((b-alpha)/(2*emean_u-emin_u-alpha)))/4/(
    emean_u-emin_u)/(cmax_u-cmin_u)
fi end proc :

NA_noinformation := (b-emin_u)^2/4/(emean_u-emin_u) :
# Int(Int((b-e)/2/(emean_u - emin_u)/(cmax_u - cmin_u),
     e = emin_u..b), c = cmin_u..cmax_u)

Offsetsupply_noinformation := proc(p)
global USA_minus_UC_noinformation, NA_noinformation, L
    :
```

```
description "Offsets supply, OS_u", "p = p_f : permit
   price":
min(USA_minus_UC_noinformation(p) + NA_noinformation, L
   )
end proc :

Creditsprice_discounted := proc(p_a)
local p_flimit :
global delta, emin_u, emean_u, b, L, NA_noinformation,
   USA_minus_UC_noinformation :
description "Discounted permits price", "p_flimit :
   offsets price",
            "L limits the amount of offset credits that
               can be sold ":
if NA_noinformation >= L then p_flimit := 0
else p_flimit := fsolve(USA_minus_UC_noinformation +
   NA_noinformation - L, 20) fi :
# if p_a = 0 then max(0, p_flimit) else
max(0, min(p_a/(1+delta), p_flimit))
# min(p_a/(1+delta), max(0, min(p_a, p_flimit)))
end proc :

Excess_noinformation := proc(p_a)
local O_n_p_fdisc, p_fdisc :
global A, delta, L, Creditsprice_discounted, Demand,
   Offsetsupply_noinformation :
description "difference between permit allocation and
   demand for permits/offsets",
            "p_fdisc : offsets price", "p_a : permit
              price":
p_fdisc := Creditsprice_discounted(p_a) :
if p_fdisc <= 0 then A + min(NA_noinformation, L) -
   Demand(p_a)
else A + Offsetsupply_noinformation(p_fdisc)/(1 + delta
   ) - Demand(p_a) fi
end proc :

Totalabatement_noinformation := proc(p_a)
CSA(p_a) + USA_noinformation(Creditsprice_discounted(
   p_a))
end proc :
```

```
Totalabatementcosts_noinformation := proc(p_a)
CSAC(p_a) + USAC_noinformation(Creditsprice_discounted(
   p_a))
end proc :

calcul_Welfare := proc(p_a)
local cpd, tanoi, tacnoi :
global SCC, Creditsprice_discounted, CSA, CSAC,
   USA_noinformation, USAC_noinformation :
cpd := Creditsprice_discounted(p_a) :
tanoi := CSA(p_a) + USA_noinformation(cpd) : #
   Totalabatement_noinformation(p_a)
tacnoi := CSAC(p_a) + USAC_noinformation(cpd) : #
   Totalabatementcosts_noinformation(p_a)
SCC*tanoi − tacnoi, tanoi, tacnoi
end proc :

point_Welfare := proc(dbL)
local p_a :
global delta, b, L, Excess_noinformation,
   calcul_Welfare :
delta, b, L := dbL[] : p_a := fsolve(
   Excess_noinformation, 20) :
if type(p_a, float) and p_a >= 0 then [dbL[], p_a,
   calcul_Welfare(p_a)]
else NULL fi
end proc :

NApct := proc(emin)
local p, ctilde_min, q_u, E_UC, E_NA :
global cmin_u, cmax_u, emean_u, alpha, NA, MCbase :
description "calculates the percent of offsets that are
    non−additional and substract off the benchmark
   level",
            "NA : percent of offsets that are non−
               additional",
            "E_NA : non−additional offset supply":
p := MCbase :
ctilde_min := p*(emean_u − alpha)/(2*emean_u − emin −
   alpha) :
E_NA := (emean_u − emin)/4 :
# Int(Int((emean_u − e)/2/(emean_u − emin)/(cmax_u −
```

```
    cmin_u), e = emin..emean_u), c = cmin_u..cmax_u)

if p <= cmin_u then q_u := 0 : E_UC := 0
elif p <= cmax_u then
        if ctilde_min <= cmin_u then
                E_UC := -(emean_u-alpha)^2*(2*ln(p/cmin_u
                    )*cmin_u*p+cmin_u^2-p^2)/4/cmin_u/(
                    cmax_u-cmin_u)/(emean_u-emin) :
                # Int(Int((e - emean_u)/(2*(emean_u -
                    emin))/(cmax_u - cmin_u), e = emean_u
                    ..(p*(emean_u-alpha)+alpha*c)/c), c =
                    cmin_u..p)
                q_u := (cmin_u-p)*((alpha-emin)^2*cmin_u-
                    p*(emean_u-alpha)^2)/4/(emean_u-emin)
                    /(cmax_u-cmin_u)/cmin_u
                # Int(Int((e-alpha)/2/(emean_u - emin)/(
                    cmax_u - cmin_u), e = emin..(p*(
                    emean_u-alpha)+alpha*c)/c), c = cmin_u
                    ..p)
        else
                E_UC := (2*p*(emean_u-alpha)^2*ln((
                    emean_u-alpha)/(2*emean_u-emin-alpha))
                    /(emean_u-emin)+2*p*(emean_u-alpha)-(
                    emean_u-emin)*cmin_u)/4/(cmax_u-cmin_u
                    ) :
                # Int(Int((e-emean_u)/2/(emean_u - emin)
                    /(cmax_u - cmin_u), e = emean_u..2*
                    emean_u-emin), c = cmin_u..ctilde_min)
                     + Int(Int((e-emean_u)/2/(emean_u -
                    emin)/(cmax_u - cmin_u), e = emean_u..
                    alpha+p*(emean_u-alpha)/c), c =
                    ctilde_min..p)
                q_u := (4*alpha*cmin_u-4*alpha*p-4*cmin_u
                    *emean_u+3*emean_u*p+emin*p)/4/(cmax_u
                    -cmin_u)
                # Int(Int((e-alpha)/2/(emean_u - emin)/(
                    cmax_u - cmin_u), e = emin..2*emean_u-
                    emin), c = cmin_u..ctilde_min) + Int(
                    Int((e-alpha)/2/(emean_u - emin)/(
                    cmax_u - cmin_u), e = emin..(p*(
                    emean_u-alpha)+alpha*c)/c), c =
                    ctilde_min..p)
```

```
        fi
else
   E_UC := E_NA :
   # Int(Int((e-emean_u)/(2*(emean_u - emin))/(cmax_u -
        cmin_u), e = emean_u..2*emean_u-emin), c =
      cmin_u..cmax_u)
   q_u := emean_u-alpha
   # Int(Int((e-alpha)/(2*(emean_u - emin))/(cmax_u -
      cmin_u), e = emin..2*emean_u-emin), c = cmin_u..
      cmax_u)
fi :

E_NA/(E_NA - E_UC + q_u) - NA
end proc :
```

A-3 Bento's data and results

Appendix 1: Bento's data

```
# ============== Input Data ============== #

# Capped sector unconstrained emissions
emean_r := 5.071E9; # tCO2eq
# Uncapped sector sequestration potential
alpha := -1.027E9; # tCO2eq
# Uncapped sector unconstrained emissions
emean_u := 0.365E9; # tCO2eq
# Marginal cost of abatement
MCbase := 25.0; # euros/tCO2eq
# Capped sector emissions reductions at a carbon price
   of MCbase
R_r := 0.864E9; # tCO2eq
# Uncapped sector emissions reductions at a carbon
   price of MCbase
R_u := 0.486E9; # tCO2eq
# Social cost of carbon
SCC := 25; # euros/tCO2eq
# Percent of offsets that are non-additional
NA := .4;
```

```
# ============ Model Calibration ============ #

# Capped sector marginal cost of abatement distribution
cmin_r := 0;
cmax_r := MCbase*emean_r/R_r;
# Uncapped sector marginal cost of abatement
   distribution
cmin_u := 0;
cmax_u := MCbase*(emean_u-alpha)/R_u;
# Uncapped sector emissions lower and upper bound
emin_u := fsolve(NApct, 0);
emax_u := 2*emean_u - emin_u;
```

Appendix 2: Bento's results

```
> restart:
>
  # ======================== DATA ======================== #

> read "/Users/mariegrappin/Desktop/Simulations_Bento/Code_Commun.
txt" ;
> read "/Users/mariegrappin/Desktop/Simulations_Bento/Data_Bento.txt"
;
```

$$emean\_r := 5.071\ 10^{9}$$

$$\alpha := -1.027\ 10^{9}$$

$$emean\_u := 3.65\ 10^{8}$$

$$MCbase := 25.0$$

$$R\_r := 8.64\ 10^{8}$$

$$R\_u := 4.86\ 10^{8}$$

$$SCC := 25$$

$$NA := 0.4$$

$$cmin\_r := 0$$

$$cmax\_r := 146.7303241$$

$$cmin\_u := 0$$

$$cmax\_u := 71.60493827$$

$$emin\_u := -5.633873788\ 10^{8}$$

$$emax\_u := 1.293387379\ 10^{9} \tag{1}$$

```
>
  # ============ Simulation: "No offsets" case ============= #

> A_nooffsets  := solve(Excess_nooffsets(p_nooffsets,A_nooffsets ),
A_nooffsets ) ;
```

$$A\_nooffsets := 5.070999999\ 10^{9} - 3.455999999\ 10^{7}\ p\_nooffsets \tag{2}$$

```
> q_r_nooffsets := Totalabatement_nooffsets(p_nooffsets) ;
```

$$q\_r\_nooffsets := 3.455999999\ 10^{7}\ p\_nooffsets \tag{3}$$

```
> C_r_nooffsets := Totalabatementcosts_nooffsets(p_nooffsets) ;
```

$$C\_r\_nooffsets := 1.728000000\ 10^{7}\ p\_nooffsets^{2} \tag{4}$$

```
> W_nooffsets := Welfare(q_r_nooffsets, C_r_nooffsets);
```

$$W\_nooffsets := 8.639999998\ 10^{8}\ p\_nooffsets - 1.728000000\ 10^{7}\ p\_nooffsets^{2} \tag{5}$$

```
> diff(W_nooffsets, p_nooffsets);
```

$$8.639999998\ 10^{8} - 3.456000000\ 10^{7}\ p\_nooffsets \tag{6}$$

```
> p_nooffsets := solve(%);
```

$$p\_nooffsets := 24.99999999 \tag{7}$$

```
> A_nooffsets ;
```

(8)

$$4.207000000\ 10^{9} \tag{8}$$

```
> R_nooffsets := Rents(p_nooffsets, A_nooffsets) ;
```

$$R\_nooffsets := 1.051750000\ 10^{11} \tag{9}$$

```
> q_r_nooffsets ;
```

$$8.639999994\ 10^{8} \tag{10}$$

```
> emean_r-q_r_nooffsets ;
```

$$4.207000001\ 10^{9} \tag{11}$$

```
> emean_u + % ;
```

$$4.572000001\ 10^{9} \tag{12}$$

```
> B_nooffsets := SCC*q_r_nooffsets;
```

$$B\_nooffsets := 2.159999998\ 10^{10} \tag{13}$$

```
> C_r_nooffsets ;
```

$$1.079999999\ 10^{10} \tag{14}$$

```
> W_nooffsets ;
```

$$1.080000000\ 10^{10} \tag{15}$$

```
>

  # ========== Simulation: "Full information" case ========= #

> A_fullinfo := solve(Excess_fullinformation(p_fullinfo, A_fullinfo),
  A_fullinfo);
```

$$A\_fullinfo := -5.399999999\ 10^{7}\ p\_fullinfo + 5.070999999\ 10^{9} \tag{16}$$

```
> Q_fullinfo := Totalabatement_fullinformation(p_fullinfo);
```

$$Q\_fullinfo := 5.399999999\ 10^{7}\ p\_fullinfo \tag{17}$$

```
> C_fullinfo := Totalabatementcosts_fullinformation(p_fullinfo);
```

$$C\_fullinfo := 2.700000000\ 10^{7}\ p\_fullinfo^{2} \tag{18}$$

```
> W_fullinfo := Welfare(Q_fullinfo,C_fullinfo);
```

$$W\_fullinfo := 1.350000000\ 10^{9}\ p\_fullinfo - 2.700000000\ 10^{7}\ p\_fullinfo^{2} \tag{19}$$

```
> diff(W_fullinfo, p_fullinfo);
```

$$1.350000000\ 10^{9} - 5.400000000\ 10^{7}\ p\_fullinfo \tag{20}$$

```
> p_fullinfo := solve(%);
```

$$p\_fullinfo := 25. \tag{21}$$

```
> A_fullinfo ;
```

$$3.720999999\ 10^{9} \tag{22}$$

```
> R_fullinfo := Rents(p_fullinfo,A_fullinfo) ;
```

$$R\_fullinfo := 9.302499998\ 10^{10} \tag{23}$$

```
> Q_fullinfo ;
```

$$1.350000000\ 10^{9} \tag{24}$$

```
> B_fullinfo := SCC*Q_fullinfo ;
```

$$B\_fullinfo := 3.375000000\ 10^{10} \tag{25}$$

```
> C_fullinfo ;
```

$$1.687500000\ 10^{10} \tag{26}$$

```
> W_fullinfo ;
```

$$1.687500000\ 10^{10} \tag{27}$$

```
> deltaW_fullinfo := (W_fullinfo-W_nooffsets)/W_nooffsets*100 ;
```

$$deltaW\_fullinfo := 56.25000000 \tag{28}$$

```
> deltacosts_fullinfo := (C_fullinfo-C_r_nooffsets)/C_r_nooffsets*100
  ;
```

$$deltacosts\_fullinfo := 56.25000014 \tag{29}$$

```
> deltaB_fullinfo := (B_fullinfo-B_nooffsets)/B_nooffsets*100 ;
```

$$deltaB\_fullinfo := 56.25000014 \tag{30}$$

```
>

  # ============= Simulation: "First-best" case ============ #

```

```
> delta := 0 ;
```

$$\delta := 0 \tag{31}$$

```
> b := emax_u ;
```

$$b := 1.293387379\ 10^{9} \tag{32}$$

```
> L := 2E9 ;
```

$$L := 2.\ 10^{9} \tag{33}$$

```
> p_a1 := SCC ;
```

$$p\_a1 := 25 \tag{34}$$

```
> p_f1 := Creditsprice_discounted(p_a1) ;
```

$$p\_f1 := 25 \tag{35}$$

```
> q_r1 := CSA(p_a1) ;
```

$$q\_r1 := 8.639999998\ 10^{8} \tag{36}$$

```
> q_u1 := USA_noinformation(p_a1) ;
```

$$q\_u1 := 4.860000000\ 10^{8} \tag{37}$$

```
> UC1 := UC_noinformation(p_a1) ;
```

$$UC1 := 0. \tag{38}$$

```
> NA1 := NA_noinformation(p_a1) ;
```

$$NA1 := 9.283873792\ 10^{8} \tag{39}$$

```
> OS1 := Offsetsupply_noinformation(p_a1) ;
```

$$OS1 := 1.414387379\ 10^{9} \tag{40}$$

```
> CSEmissions1 := emean_r-CSA(p_a1) ;
```

$$CSEmissions1 := 4.207000000\ 10^{9} \tag{41}$$

```
> USEmissions1 := emean_u-USA_noinformation(p_a1) ;
```

$$USEmissions1 := -1.210000000\ 10^{8} \tag{42}$$

```
> CSEmissions1 + USEmissions1 ;
```

$$4.086000000\ 10^{9} \tag{43}$$

```
> A1 := solve(Excess_noinformation(p_a1),A) ;
```

$$A1 := 2.792612621\ 10^{9} \tag{44}$$

```
> Q1 := Totalabatement_noinformation(p_a1) ;
                        Q1 := 1.350000000 10^9                        (45)
> B1 := SCC*Q1 ;
                        B1 := 3.375000000 10^10                       (46)
> C1 := Totalabatementcosts_noinformation(p_a1) ;
                        C1 := 1.687500000 10^10                       (47)
> W1 := Welfare(Q1,C1) ;
                        W1 := 1.687500000 10^10                       (48)
> R1 := Rents(A1,p_a1) ;
                        R1 := 6.981531552 10^10                       (49)
> (R_nooffsets-R1);
                              3.535968448 10^10                       (50)
> (W1-W_nooffsets);
                              6.07500000 10^9                         (51)
> %/%%;
                              0.1718058317                            (52)
> deltaW_1 := (W1-W_nooffsets)/W_nooffsets*100 ;
                        deltaW_1 := 56.25000000                       (53)
> deltacosts_1 := (C1-C_r_nooffsets)/C_r_nooffsets*100 ;
                      deltacosts_1 := 56.25000014                     (54)
> deltaB_1 := (B1-B_nooffsets)/B_nooffsets*100 ;
                        deltaB_1 := 56.25000014                       (55)
>

  # ========= "Second best" case: parameters' list ========= #


> n := 60 :
> delta_liste := [seq(-0.99 + i*1.98/n, i = 0..n), 1] :
  b_liste := sort([seq(emin_u + i*(emax_u-emin_u)/n, i = 0..n),
  emean_u]) :
  L_liste := [seq(A/50 + i*(2E9 - A/50)/n, i = 0..n)] :
> # sigma := [seq(seq(seq(point_Welfare([dd,bb,LL]), dd in
  delta_liste), bb in b_liste), LL in L_liste)] :
> # save sigma,
  "/Users/mariegrappin/Desktop/Simulations_Bento/sauvegarde_sigma.
  txt" :
> read
  "/Users/mariegrappin/Desktop/Simulations_Bento/sauvegarde_sigma.
  txt" :
> A := A_nooffsets ; # A's value is set and equals the no-offsets
  value (tCO2eq)
                        A := 4.207000000 10^9                         (56)
>

  # ========= Simulation: "Unrestricted" setting ======== #
```

```
> p := 'p': p_a := 'p_a': delta := 'delta' : b := 'b': L := 'L':
> MW := 0: for ll in sigma do w := ll[5] : if w > MW then MW := w :
  maxW := ll fi od : maxW ;
```

$$\left[-0.3300000000, -4.396023949\ 10^{8}, 1.480020000\ 10^{8}, 19.67889513, 1.454315190\ 10^{10}, 9.193535512\ 10^{8}, 8.440686884\ 10^{9}\right] \tag{57}$$

```
> delta := maxW[1] ;
```

$$\delta := -0.3300000000 \tag{58}$$

```
> b :=  maxW[2] ;#tCO2eq
```

$$b := -4.396023949\ 10^{8} \tag{59}$$

```
> L := maxW[3] ; #tCO2eq
```

$$L := 1.480020000\ 10^{8} \tag{60}$$

```
> p_a2 := fsolve(Excess_noinformation, 20) ;
```

$$p\_a2 := 19.67889513 \tag{61}$$

```
> p_f2 := Creditsprice_discounted(p_a2) ;
```

$$p\_f2 := 29.37148527 \tag{62}$$

```
> q_r2 := CSA(p_a2) ;
```

$$q\_r2 := 6.801026155\ 10^{8} \tag{63}$$

```
> q_u2 := USA_noinformation(p_f2) ;
```

$$q\_u2 := 2.392509357\ 10^{8} \tag{64}$$

```
> UN2 := UC_noinformation(p_f2) ;
```

$$UN2 := 1.201658542\ 10^{8} \tag{65}$$

```
> NA2 := NA_noinformation(p_f2) ;
```

$$NA2 := 4.126166132\ 10^{6} \tag{66}$$

```
> OS2 := Offsetsupply_noinformation(p_f2) ;
```

$$OS2 := 1.232112477\ 10^{8} \tag{67}$$

```
> CSEmissions2 := emean_r - q_r2 ;
```

$$CSEmissions2 := 4.390897384\ 10^{9} \tag{68}$$

```
> USEmissions2 := emean_u - q_u2 ;
```

$$USEmissions2 := 1.257490643\ 10^{8} \tag{69}$$

```
> CSEmissions2 + USEmissions2 ;
```

$$4.516646448\ 10^{9} \tag{70}$$

```
> Q2 := Totalabatement_noinformation(p_a2) ;
```

$$Q2 := 9.193535512\ 10^{8} \tag{71}$$

```
> B2 := SCC*Q2 ;
```

$$B2 := 2.298383878\ 10^{10} \tag{72}$$

```
> C2 := Totalabatementcosts_noinformation(p_a2) ;
```

$$C2 := 8.440686884\ 10^{9} \tag{73}$$

```
> W2 := Welfare(Q2, C2) ;
```

$$W2 := 1.454315190\ 10^{10} \tag{74}$$

```
> R2 := Rents(p_a2, A) ;
```

$$R2 := 8.278911181\ 10^{10} \tag{75}$$

```
> R2 - R1 ;
```

$$1.297379629\ 10^{10} \tag{76}$$

```
> W1 - W2 ;
```

$$2.33184810\ 10^{9} \tag{77}$$

```
> %/%% ;
```

$$0.1797352177 \tag{78}$$

```
> deltaW_2 := 100*(W2-W_nooffsets)/W_nooffsets ; #%
```

$$deltaW\_2 := 34.65881389 \tag{79}$$

```
> deltacosts_2 := 100*(C2-C_r_nooffsets)/C_r_nooffsets ; #%
```

$$deltacosts\_2 := -21.84549174 \tag{80}$$

```
> deltaB_2 := 100*(B2-B_nooffsets)/B_nooffsets ; #%
```

$$deltaB\_2 := 6.406661117 \tag{81}$$

```
>

  # ========= Simulation: "Baseline" setting ======== #

> p := 'p': p_a := 'p_a': delta := 'delta' : b := 'b': L := 'L':
> ll := 'll': sigma_baseline := select(ll -> ll[1] >= 0, sigma) :
> MW := 0: for ll in sigma_baseline do w := ll[5] : if w > MW then MW
  := w : maxW := ll fi od : maxW ;
```

$$\left[0., -2.229786731\ 10^{8}, 1.799330000\ 10^{8}, 20.14695791, 1.445386807\ 10^{10}, 9.137207891\ 10^{8}, 8.389151660\ 10^{9}\right] \tag{82}$$

```
> delta := maxW[1] ;
```

$$\delta := 0. \tag{83}$$

```
> b :=  maxW[2] ;#tCO2eq
```

$$b := -2.229786731\ 10^{8} \tag{84}$$

```
> L := maxW[3] ; #tCO2eq
```

$$L := 1.799330000\ 10^{8} \tag{85}$$

```
> p_a2 := fsolve(Excess_noinformation, 20) ;
```

$$p\_a2 := 20.14695791 \tag{86}$$

```
> p_f2 := Creditsprice_discounted(p_a2) ;
```

$$p\_f2 := 20.14695791 \tag{87}$$

```
> Excess_noinformation(0.1) ;
```

$$-8.28662263\ 10^{8} \tag{88}$$

```
> q_r2 := CSA(p_a2) ;
```

$$q\_r2 := 6.962788655\ 10^{8} \tag{89}$$

```
> q_u2 := USA_noinformation(p_f2) ;
```

$$q\_u2 := 2.174419236\ 10^{8} \tag{90}$$

```
> UN2 := UC_noinformation(p_f2) ;
```

$$UN2 := 8.092492015\ 10^{7} \tag{91}$$

```
> NA2 := NA_noinformation(p_f2) ;
```

$$NA2 := 3.120413138\ 10^{7} \tag{92}$$

```
> OS2 := Offsetsupply_noinformation(p_f2) ;
                    OS2 := 1.677211348 10^8                              (93)
> CSEmissions2 := emean_r - q_r2 ;
              CSEmissions2 := 4.374721134 10^9                           (94)
> USEmissions2 := emean_u - q_u2 ;
              USEmissions2 := 1.475580764 10^8                           (95)
> CSEmissions2 + USEmissions2 ;
                         4.522279210 10^9                                (96)
> Q2 := Totalabatement_noinformation(p_a2) ;
                    Q2 := 9.137207891 10^8                               (97)
> B2 := SCC*Q2 ;
                    B2 := 2.284301973 10^10                              (98)
> C2 := Totalabatementcosts_noinformation(p_a2) ;
                    C2 := 8.389151660 10^9                               (99)
> W2 := Welfare(Q2, C2) ;
                    W2 := 1.445386807 10^10                             (100)
> R2 := Rents(p_a2, A) ;
                    R2 := 8.475825193 10^10                             (101)
> R2 - R1 ;
                         1.494293641 10^10                              (102)
> W1 - W2 ;
                         2.42113193 10^9                                (103)
> %/%% ;
                         0.1620251779                                   (104)
> deltaW_2 := 100*(W2-W_nooffsets)/W_nooffsets ; #%
                    deltaW_2 := 33.83211176                             (105)
> deltacosts_2 := 100*(C2-C_r_nooffsets)/C_r_nooffsets ; #%
                 deltacosts_2 := -22.32266974                           (106)
> deltaB_2 := 100*(B2-B_nooffsets)/B_nooffsets ; #%
                    deltaB_2 := 5.754721070                             (107)
> 

  # ========= Simulation: "Ratio" setting ======== #

> p := 'p': p_a := 'p_a': delta := 'delta' : b := 'b': L := 'L':
> ll := 'll' : sigma_ratio := select(ll -> ll[2] = 365000000.2,
  sigma) :
> MW := 0 : for ll in sigma_ratio do w := ll[5] : if w > MW then MW
  := w : maxW := ll fi od : maxW ;
[0.792000000, 3.650000002 10^8, 4.034500000 10^8, 18.88295104, 1.364755392 10^10,   (108)

    8.232857855 10^8, 6.934590717 10^9]

> delta := maxW[1] ;
```

$$\delta := 0.792000000 \tag{109}$$

```
> b :=  maxW[2] ;#tCO2eq
```

$$b := 3.650000002\ 10^{8} \tag{110}$$

```
> L := maxW[3] ; #tCO2eq
```

$$L := 4.034500000\ 10^{8} \tag{111}$$

```
> p_a2 := fsolve(Excess_noinformation, 20) ;
```

$$p\_a2 := 18.88295104 \tag{112}$$

```
> p_f2 := Creditsprice_discounted(p_a2) ;
```

$$p\_f2 := 10.53736107 \tag{113}$$

```
> Excess_noinformation(0.1) ;
```

$$-7.30592016\ 10^{8} \tag{114}$$

```
> q_r2 := CSA(p_a2) ;
```

$$q\_r2 := 6.525947878\ 10^{8} \tag{115}$$

```
> q_u2 := USA_noinformation(p_f2) ;
```

$$q\_u2 := 1.706909977\ 10^{8} \tag{116}$$

```
> UN2 := UC_noinformation(p_f2) ;
```

$$UN2 := 2.394970235\ 10^{7} \tag{117}$$

```
> NA2 := NA_noinformation(p_f2) ;
```

$$NA2 := 2.320968448\ 10^{8} \tag{118}$$

```
> OS2 := Offsetsupply_noinformation(p_f2) ;
```

$$OS2 := 3.788381402\ 10^{8} \tag{119}$$

```
> CSEmissions2 := emean_r - q_r2 ;
```

$$CSEmissions2 := 4.418405212\ 10^{9} \tag{120}$$

```
> USEmissions2 := emean_u - q_u2 ;
```

$$USEmissions2 := 1.943090023\ 10^{8} \tag{121}$$

```
> CSEmissions2 + USEmissions2 ;
```

$$4.612714214\ 10^{9} \tag{122}$$

```
> Q2 := Totalabatement_noinformation(p_a2) ;
```

$$Q2 := 8.232857855\ 10^{8} \tag{123}$$

```
> B2 := SCC*Q2 ;
```

$$B2 := 2.058214464\ 10^{10} \tag{124}$$

```
> C2 := Totalabatementcosts_noinformation(p_a2) ;
```

$$C2 := 6.934590717\ 10^{9} \tag{125}$$

```
> W2 := Welfare(Q2, C2) ;
```

$$W2 := 1.364755392\ 10^{10} \tag{126}$$

```
> R2 := Rents(p_a2, A) ;
```

$$R2 := 7.944057503\ 10^{10} \tag{127}$$

```
> R2 - R1 ;
```

$$9.62525951\ 10^{9} \tag{128}$$

```
> W1 - W2 ;
```

(129)

$$3.22744608\ 10^{9} \tag{129}$$

```
> %/%% ;
```

$$0.3353100326 \tag{130}$$

```
> deltaW_2 := 100*(W2-W_nooffsets)/W_nooffsets ; #%
```

$$deltaW\_2 := 26.36624000 \tag{131}$$

```
> deltacosts_2 := 100*(C2-C_r_nooffsets)/C_r_nooffsets ; #%
```

$$deltacosts\_2 := -35.79082663 \tag{132}$$

```
> deltaB_2 := 100*(B2-B_nooffsets)/B_nooffsets ; #%
```

$$deltaB\_2 := -4.712293245 \tag{133}$$

```
>

  # ========= Simulation: "Limit" setting ======== #

> p := 'p': p_a := 'p_a': L := 'L': delta := 'delta' : b := 'b':
> sigma_limit := select(ll -> ll[1] = 0, sigma_ratio) :
> MW := 0: for ll in sigma_limit do w := ll[5] : if w > MW then MW :=
  w : maxW := ll fi od : maxW ;
```

$$[0., 3.650000002\ 10^{8}, 4.353810000\ 10^{8}, 13.03274394, 1.242039538\ 10^{10}, 6.615244557\ 10^{8}, 4.117716009\ 10^{9}] \tag{134}$$

```
> delta := maxW[1] ;
```

$$\delta := 0. \tag{135}$$

```
> b :=  maxW[2] ;#tCO2eq
```

$$b := 3.650000002\ 10^{8} \tag{136}$$

```
> L := maxW[3] ; #tCO2eq
```

$$L := 4.353810000\ 10^{8} \tag{137}$$

```
> p_a2 := fsolve(Excess_noinformation, 20) ;
```

$$p\_a2 := 13.03274394 \tag{138}$$

```
> p_f2 := Creditsprice_discounted(p_a2) ;
```

$$p\_f2 := 13.03274394 \tag{139}$$

```
> Excess_noinformation(0.1) ;
```

$$-6.27054574\ 10^{8} \tag{140}$$

```
> q_r2 := CSA(p_a2) ;
```

$$q\_r2 := 4.504116305\ 10^{8} \tag{141}$$

```
> q_u2 := USA_noinformation(p_f2) ;
```

$$q\_u2 := 2.111128252\ 10^{8} \tag{142}$$

```
> UN2 := UC_noinformation(p_f2) ;
```

$$UN2 := 2.962130045\ 10^{7} \tag{143}$$

```
> NA2 := NA_noinformation(p_f2) ;
```

$$NA2 := 2.320968448\ 10^{8} \tag{144}$$

```
> OS2 := Offsetsupply_noinformation(p_f2) ;
```

$$OS2 := 4.135883696\ 10^{8} \tag{145}$$

```
> CSEmissions2 := emean_r - q_r2 ;
```

$$CSEmissions2 := 4.620588370\ 10^{9} \tag{146}$$

```
> USEmissions2 := emean_u - q_u2 ;
```

$$USEmissions2 := 1.538871748\ 10^{8} \tag{147}$$

```
> CSEmissions2 + USEmissions2 ;
```

$$4.774475545\ 10^{9} \tag{148}$$

```
> Q2 := Totalabatement_noinformation(p_a2) ;
```

$$Q2 := 6.615244557\ 10^{8} \tag{149}$$

```
> B2 := SCC*Q2 ;
```

$$B2 := 1.653811139\ 10^{10} \tag{150}$$

```
> C2 := Totalabatementcosts_noinformation(p_a2) ;
```

$$C2 := 4.117716009\ 10^{9} \tag{151}$$

```
> W2 := Welfare(Q2, C2) ;
```

$$W2 := 1.242039538\ 10^{10} \tag{152}$$

```
> R2 := Rents(p_a2, A) ;
```

$$R2 := 5.482875376\ 10^{10} \tag{153}$$

```
> R2 - R1 ;
```

$$-1.498656176\ 10^{10} \tag{154}$$

```
> W1 - W2 ;
```

$$4.45460462\ 10^{9} \tag{155}$$

```
> %/%% ;
```

$$-0.2972399334 \tag{156}$$

```
> deltaW_2 := 100*(W2-W_nooffsets)/W_nooffsets ; #%
```

$$deltaW\_2 := 15.00366093 \tag{157}$$

```
> deltacosts_2 := 100*(C2-C_r_nooffsets)/C_r_nooffsets ; #%
```

$$deltacosts\_2 := -61.87299988 \tag{158}$$

```
> deltaB_2 := 100*(B2-B_nooffsets)/B_nooffsets ; #%
```

$$deltaB\_2 := -23.43466942 \tag{159}$$

A-4 EU ETS's data and results

Appendix 1: EU ETS's data

```
# ======================== Input Data ======================== #

# Capped sector unconstrained emissions
emean_r := 1.333E9; # tCO2eq
# Uncapped sector sequestration potential
alpha := -1.556E9; # tCO2eq
# Uncapped sector unconstrained emissions
emean_u := 0.503E9; # tCO2eq
# Marginal cost of abatement
MCbase := 25; # euros/tCO2eq
# Capped sector emissions reductions at a carbon price
    of MCbase
R_r := 0.110E9; # tCO2eq
# Uncapped sector emissions reductions at a carbon
    price of MCbase
R_u := 0.252E9; # tCO2eq
# Social cost of carbon
SCC := 40; # euros/tCO2eq
# Percent of offsets that are non-additional
NA := .4;


# ==================== Model Calibration ==================== #

# Capped sector marginal cost of abatement distribution
cmin_r := 0;
cmax_r := MCbase*emean_r/R_r;
# Uncapped sector marginal cost of abatement
    distribution
cmin_u := 0;
cmax_u := MCbase*(emean_u-alpha)/R_u;
# Uncapped sector emissionss lower and upper bound
emin_u := fsolve(NApct, 0);
emax_u := 2*emean_u - emin_u;
```

Appendix 2: EU ETS's results

```
> restart:
>

  # ======================== DATA ======================== #

> read "/Users/mariegrappin/Desktop/Simulations_Bento/Code_Commun.
  txt" ;
> read "/Users/mariegrappin/Desktop/Simulations_EUETS/Data_EUETS.txt"
  ;
```

$$emean\_r := 1.333\ 10^{9}$$

$$\alpha := -1.556\ 10^{9}$$

$$emean\_u := 5.03\ 10^{8}$$

$$MCbase := 25$$

$$R\_r := 1.10\ 10^{8}$$

$$R\_u := 2.52\ 10^{8}$$

$$SCC := 40$$

$$NA := 0.4$$

$$cmin\_r := 0$$

$$cmax\_r := 302.9545455$$

$$cmin\_u := 0$$

$$cmax\_u := 204.2658730$$

$$emin\_u := -8.112717851\ 10^{7}$$

$$emax\_u := 1.087127179\ 10^{9} \tag{1}$$

```
>

  # ============ Simulation: "No offsets" case ============= #

> A_nooffsets  := solve(Excess_nooffsets(p_nooffsets,A_nooffsets ),
  A_nooffsets ) ;
```

$$A\_nooffsets := 1.333000000\ 10^{9} - 4.399999999\ 10^{6}\ p\_nooffsets \tag{2}$$

```
> q_r_nooffsets := Totalabatement_nooffsets(p_nooffsets) ;
```

$$q\_r\_nooffsets := 4.399999999\ 10^{6}\ p\_nooffsets \tag{3}$$

```
> C_r_nooffsets := Totalabatementcosts_nooffsets(p_nooffsets) ;
```

$$C\_r\_nooffsets := 2.200000000\ 10^{6}\ p\_nooffsets^{2} \tag{4}$$

```
> W_nooffsets := Welfare(q_r_nooffsets, C_r_nooffsets);
```

$$W\_nooffsets := 1.760000000\ 10^{8}\ p\_nooffsets - 2.200000000\ 10^{6}\ p\_nooffsets^{2} \tag{5}$$

```
> diff(W_nooffsets, p_nooffsets);
```

$$1.760000000\ 10^{8} - 4.400000000\ 10^{6}\ p\_nooffsets \tag{6}$$

```
> p_nooffsets := solve(%);
```

$$p\_nooffsets := 40. \tag{7}$$

```
> A_nooffsets ;
```

$$1.157000000\ 10^{9} \tag{8}$$

```
> q_r_nooffsets ;
```

$$1.760000000\ 10^{8} \tag{9}$$

```
> emean_r-q_r_nooffsets ;
```

$$1.157000000\ 10^{9} \tag{10}$$

```
> emean_u + % ;
```

$$1.660000000\ 10^{9} \tag{11}$$

```
> B_nooffsets := SCC*q_r_nooffsets;
```

$$B\_nooffsets := 7.040000000\ 10^{9} \tag{12}$$

```
> C_r_nooffsets ;
```

$$3.520000000\ 10^{9} \tag{13}$$

```
> W_nooffsets ;
```

$$3.520000000\ 10^{9} \tag{14}$$

```
>

  # ============= Simulation: "First-best" case ============ #

> delta := 0 ;
```

$$\delta := 0 \tag{15}$$

```
> b := emax_u ;
```

$$b := 1.087127179\ 10^{9} \tag{16}$$

```
> L := 10E9 ;
```

$$L := 1.0\ 10^{10} \tag{17}$$

```
> p_a1 := SCC ;
```

$$p\_a1 := 40 \tag{18}$$

```
> p_f1 := Creditsprice_discounted(p_a1) ;
```

$$p\_f1 := 40 \tag{19}$$

```
> q_r1 := CSA(p_a1) ;
```

$$q\_r1 := 1.760000000\ 10^{8} \tag{20}$$

```
> q_u1 := USA_noinformation(p_a1) ;
```

$$q\_u1 := 4.032000010\ 10^{8} \tag{21}$$

```
> UC1 := UC_noinformation(p_a1) ;
```

$$UC1 := 0. \tag{22}$$

```
> NA1 := NA_noinformation(p_a1) ;
```

$$NA1 := 5.841271795\ 10^{8} \tag{23}$$

```
> OS1 := Offsetsupply_noinformation(p_a1) ;
```

$$OS1 := 9.873271797\ 10^{8} \tag{24}$$

```
> CSEmissions1 := emean_r-CSA(p_a1) ;
```

$$CSEmissions1 := 1.157000000\ 10^{9} \tag{25}$$

```
> USEmissions1 := emean_u-USA_noinformation(p_a1) ;
```

$$USEmissions1 := 9.97999990\ 10^{7} \tag{26}$$

```
> CSEmissions1 + USEmissions1 ;
```

$$1.256799999\ 10^{9} \tag{27}$$

```
> A1 := solve(Excess_noinformation(p_a1),A) ;
```

$$A1 := 1.696728203\ 10^{8} \tag{28}$$

```
> Q1 := Totalabatement_noinformation(p_a1) ;
```

$$Q1 := 5.792000010\ 10^{8} \tag{29}$$

```
> B1 := SCC*Q1 ;
```

$$B1 := 2.316800004\ 10^{10} \tag{30}$$

```
> C1 := Totalabatementcosts_noinformation(p_a1) ;
```

$$C1 := 1.158400001\ 10^{10} \tag{31}$$

```
> W1 := Welfare(Q1,C1) ;
```

$$W1 := 1.158400003\ 10^{10} \tag{32}$$

```
> (W1-W_nooffsets);
```

$$8.064000030\ 10^{9} \tag{33}$$

```
> %/%%;
```

$$0.6961325975 \tag{34}$$

```
> deltaW_1 := (W1-W_nooffsets)/W_nooffsets*100 ;
```

$$deltaW\_1 := 229.0909099 \tag{35}$$

```
> deltacosts_1 := (C1-C_r_nooffsets)/C_r_nooffsets*100 ;
```

$$deltacosts\_1 := 229.0909094 \tag{36}$$

```
> deltaB_1 := (B1-B_nooffsets)/B_nooffsets*100 ;
```

$$deltaB\_1 := 229.0909097 \tag{37}$$

```
> 

  # ========= "Second-best" cases: parameters' list ========= #

> n := 60 :
> A := A_nooffsets ; # A's value is set and equals the no-offsets
  value (tCO2eq)
```

$$A := 1.157000000\ 10^{9} \tag{38}$$

```
> #delta_liste := [seq(-0.99 + i*1.98/n, i = 0..n), 0] :
  #b_liste := sort([seq(emin_u + i*(emax_u-emin_u)/n, i = 0..n),
  emean_u]) :
  #L_liste := [seq(A/50 + i*(10E9 - A/50)/n, i = 0..n)] :
> #sigma := [seq(seq(seq(point_Welfare([dd,bb,LL]), dd in
  delta_liste), bb in b_liste), LL in L_liste)] :
> #save sigma,
  "/Users/mariegrappin/Desktop/Simulations_EUETS/sauvegarde_sigma.
  txt" :
> read
  "/Users/mariegrappin/Desktop/Simulations_EUETS/sauvegarde_sigma.
  txt" :

> 

  # ========= Simulation: "Unrestricted" setting ======== #
```

```
> p := 'p': p_a := 'p_a': delta := 'delta' : b := 'b': L := 'L':
> MW := 0: for ll in sigma do w := ll[5] : if w > MW then MW := w :
  maxW := ll fi od : maxW ;
```

$$[0.528000000, -8.112717851\ 10^{7}, 1.894210000\ 10^{8}, 26.35653733, 7.301146142\ 10^{9}, 2.405130357\ 10^{8}, 2.319375286\ 10^{9}] \tag{39}$$

```
> delta := maxW[1] ;
```

$$\delta := 0.528000000 \tag{40}$$

```
> b := maxW[2] ;#tCO2eq
```

$$b := -8.112717851\ 10^{7} \tag{41}$$

```
> L := maxW[3] ; #tCO2eq
```

$$L := 1.894210000\ 10^{8} \tag{42}$$

```
> p_a2 := fsolve(Excess_noinformation, 20) ;
```

$$p\_a2 := 26.35653733 \tag{43}$$

```
> p_f2 := Creditsprice_discounted(p_a2) ;
```

$$p\_f2 := 17.24904276 \tag{44}$$

```
> q_r2 := CSA(p_a2) ;
```

$$q\_r2 := 1.159687642\ 10^{8} \tag{45}$$

```
> q_u2 := USA_noinformation(p_f2) ;
```

$$q\_u2 := 1.245442715\ 10^{8} \tag{46}$$

```
> UC2 := UC_noinformation(p_f2) ;
```

$$UC2 := 3.281654338\ 10^{7} \tag{47}$$

```
> NA2 := NA_noinformation(p_f2) ;
```

$$NA2 := 0. \tag{48}$$

```
> OS2 := Offsetsupply_noinformation(p_f2) ;
```

$$OS2 := 9.172772825\ 10^{7} \tag{49}$$

```
> CSEmissions2 := emean_r - q_r2 ;
```

$$CSEmissions2 := 1.217031236\ 10^{9} \tag{50}$$

```
> USEmissions2 := emean_u - q_u2 ;
```

$$USEmissions2 := 3.784557285\ 10^{8} \tag{51}$$

```
> CSEmissions2 + USEmissions2 ;
```

$$1.595486964\ 10^{9} \tag{52}$$

```
> Q2 := Totalabatement_noinformation(p_a2) ;
```

$$Q2 := 2.405130357\ 10^{8} \tag{53}$$

```
> B2 := SCC*Q2 ;
```

$$B2 := 9.620521428\ 10^{9} \tag{54}$$

```
> C2 := Totalabatementcosts_noinformation(p_a2) ;
```

$$C2 := 2.319375286\ 10^{9} \tag{55}$$

```
> W2 := Welfare(Q2, C2) ;
```

$$W2 := 7.301146142\ 10^{9} \tag{56}$$

```
> W1 - W2 ;
```

$$4.282853888\ 10^{9} \tag{57}$$

```
> %/%% ;
```

$$0.5866002138 \tag{58}$$

```
> deltaW_2 := 100*(W2-W_nooffsets)/W_nooffsets ; #%
```

$$deltaW\_2 := 107.4189245 \tag{59}$$

```
> deltacosts_2 := 100*(C2-C_r_nooffsets)/C_r_nooffsets ; #%
```

$$deltacosts\_2 := -34.10865665 \tag{60}$$

```
> deltaB_2 := 100*(B2-B_nooffsets)/B_nooffsets ; #%
```

$$deltaB\_2 := 36.65513392 \tag{61}$$

```
>

  # =============== Simulation: "Ratio" setting =============== #

> p := 'p': p_a := 'p_a': delta := 'delta' : b := 'b': L := 'L':
> ll := 'll' : sigma_ratio := select(ll -> ll[2] = emean_u, sigma) :
> MW := 0 : for ll in sigma_ratio do w := ll[5] : if w > MW then MW
  := w : maxW := ll fi od : maxW ;
```

$$[0.99, 5.03\ 10^{8}, 3.557020000\ 10^{8}, 15.51855699, 4.856290522\ 10^{9}, 1.413131467\ 10^{8}, 7.962353455\ 10^{8}] \tag{62}$$

```
> delta := maxW[1] ;
```

$$\delta := 0.99 \tag{63}$$

```
> b :=  maxW[2] ;#tCO2eq
```

$$b := 5.03\ 10^{8} \tag{64}$$

```
> L := maxW[3] ; #tCO2eq
```

$$L := 3.557020000\ 10^{8} \tag{65}$$

```
> p_a2 := fsolve(Excess_noinformation, 20) ;
```

$$p\_a2 := 15.51855699 \tag{66}$$

```
> p_f2 := Creditsprice_discounted(p_a2) ;
```

$$p\_f2 := 7.798269844 \tag{67}$$

```
> q_r2 := CSA(p_a2) ;
```

$$q\_r2 := 6.828165075\ 10^{7} \tag{68}$$

```
> q_u2 := USA_noinformation(p_f2) ;
```

$$q\_u2 := 7.303149598\ 10^{7} \tag{69}$$

```
> UC2 := UC_noinformation(p_f2) ;
```

$$UC2 := 4.703775515\ 10^{6} \tag{70}$$

```
> NA2 := NA_noinformation(p_f2) ;
```

$$NA2 := 1.460317946\ 10^{8} \tag{71}$$

```
> OS2 := Offsetsupply_noinformation(p_f2) ;
```

$$OS2 := 2.143595150\ 10^{8} \tag{72}$$

```
> CSEmissions2 := emean_r - q_r2 ;
```

$$CSEmissions2 := 1.264718349\ 10^{9} \tag{73}$$

```
> USEmissions2 := emean_u - q_u2 ;
```

$$USEmissions2 := 4.299685040\ 10^{8} \tag{74}$$

```
> CSEmissions2 + USEmissions2 ;
                              1.694686853 10^9                          (75)
> Q2 := Totalabatement_noinformation(p_a2) ;
                           Q2 := 1.413131467 10^8                       (76)
> B2 := SCC*Q2 ;
                           B2 := 5.652525868 10^9                       (77)
> C2 := Totalabatementcosts_noinformation(p_a2) ;
                           C2 := 7.962353455 10^8                       (78)
> W2 := Welfare(Q2, C2) ;
                           W2 := 4.856290522 10^9                       (79)
> W1 - W2 ;
                              6.727709508 10^9                          (80)
> %/%% ;
                                1.385359767                             (81)
> deltaW_2 := 100*(W2-W_nooffsets)/W_nooffsets ; #%
                          deltaW_2 := 37.96279892                       (82)
> deltacosts_2 := 100*(C2-C_r_nooffsets)/C_r_nooffsets ; #%
                        deltacosts_2 := -77.37967767                    (83)
> deltaB_2 := 100*(B2-B_nooffsets)/B_nooffsets ; #%
                          deltaB_2 := -19.70843938                      (84)
>

  # =============== Simulation: "Limit" setting =============== #

> p := 'p': p_a := 'p_a': L := 'L': delta := 'delta' : b := 'b':
> sigma_limit := select(ll -> ll[1] = 0, sigma_ratio) :
> MW := 0: for ll in sigma_limit do w := ll[5] : if w > MW then MW :=
  w : maxW := ll fi od : maxW ;
[0., 5.03 10^8, 2.314000000 10^7, 34.74090910, 3.459152317 10^9, 1.528600000 10^8,     (85)

    2.655247683 10^9]

> delta := maxW[1] ;
                                 δ := 0.                                (86)
> b :=  maxW[2] ;#tCO2eq
                               b := 5.03 10^8                           (87)
> L := maxW[3] ; #tCO2eq
                           L := 2.314000000 10^7                        (88)
> p_a2 := fsolve(Excess_noinformation, 20) ;
                            p_a2 := 34.74090910                         (89)
> p_f2 := Creditsprice_discounted(p_a2) ;
                                p_f2 := 0                               (90)
> q_r2 := CSA(p_a2) ;
                          q_r2 := 1.528600000 10^8                      (91)
```

```
> q_u2 := USA_noinformation(p_f2) ;
```

$$q\_u2 := 0. \tag{92}$$

```
> UC2 := UC_noinformation(p_f2) ;
```

$$UC2 := 0. \tag{93}$$

```
> NA2 := NA_noinformation(p_f2) ;
```

$$NA2 := 1.460317946\ 10^{8} \tag{94}$$

```
> OS2 := Offsetsupply_noinformation(p_f2) ;
```

$$OS2 := 2.314000000\ 10^{7} \tag{95}$$

```
> CSEmissions2 := emean_r - q_r2 ;
```

$$CSEmissions2 := 1.180140000\ 10^{9} \tag{96}$$

```
> USEmissions2 := emean_u - q_u2 ;
```

$$USEmissions2 := 5.03\ 10^{8} \tag{97}$$

```
> CSEmissions2 + USEmissions2 ;
```

$$1.683140000\ 10^{9} \tag{98}$$

```
> Q2 := Totalabatement_noinformation(p_a2) ;
```

$$Q2 := 1.528600000\ 10^{8} \tag{99}$$

```
> B2 := SCC*Q2 ;
```

$$B2 := 6.114400000\ 10^{9} \tag{100}$$

```
> C2 := Totalabatementcosts_noinformation(p_a2) ;
```

$$C2 := 2.655247683\ 10^{9} \tag{101}$$

```
> W2 := Welfare(Q2, C2) ;
```

$$W2 := 3.459152317\ 10^{9} \tag{102}$$

```
> W1 - W2 ;
```

$$8.124847713\ 10^{9} \tag{103}$$

```
> %/%% ;
```

$$2.348797326 \tag{104}$$

```
> deltaW_2 := 100*(W2-W_nooffsets)/W_nooffsets ; #%
```

$$deltaW\_2 := -1.728627358 \tag{105}$$

```
> deltacosts_2 := 100*(C2-C_r_nooffsets)/C_r_nooffsets ; #%
```

$$deltacosts\_2 := -24.56682719 \tag{106}$$

```
> deltaB_2 := 100*(B2-B_nooffsets)/B_nooffsets ; #%
```

$$deltaB\_2 := -13.14772727 \tag{107}$$

```
>

  # =============== Simulation: "Alike situation" case ==============
  = #
```

```
> delta := maxW[1] ;
```

$$\delta := 0. \tag{108}$$

```
> b :=  maxW[2] ;#tCO2eq
```

$$b := 5.03\ 10^{8} \tag{109}$$

```
> L := A/50 + 1*(10E9 - A/50)/60 ; #maxW[3] ; #tCO2eq
```

$$L := 1.894210000\ 10^{8} \tag{110}$$

```
> p_a2 := fsolve(Excess_noinformation, 20) ;
```

$$p\_a2 := 2.276889195 \tag{111}$$

```
> p_f2 := Creditsprice_discounted(p_a2) ;
```

$$p\_f2 := 2.276889195 \tag{112}$$

```
> q_r2 := CSA(p_a2) ;
```

$$q\_r2 := 1.001831246\ 10^{7} \tag{113}$$

```
> q_u2 := USA_noinformation(p_f2) ;
```

$$q\_u2 := 2.132327140\ 10^{7} \tag{114}$$

```
> UC2 := UC_noinformation(p_f2) ;
```

$$UC2 := 1.373378440\ 10^{6} \tag{115}$$

```
> NA2 := NA_noinformation(p_f2) ;
```

$$NA2 := 1.460317946\ 10^{8} \tag{116}$$

```
> OS2 := Offsetsupply_noinformation(p_f2) ;
```

$$OS2 := 1.659816875\ 10^{8} \tag{117}$$

```
> CSEmissions2 := emean_r - q_r2 ;
```

$$CSEmissions2 := 1.322981688\ 10^{9} \tag{118}$$

```
> USEmissions2 := emean_u - q_u2 ;
```

$$USEmissions2 := 4.816767286\ 10^{8} \tag{119}$$

```
> CSEmissions2 + USEmissions2 ;
```

$$1.804658417\ 10^{9} \tag{120}$$

```
> Q2 := Totalabatement_noinformation(p_a2) ;
```

$$Q2 := 3.134158386\ 10^{7} \tag{121}$$

```
> B2 := SCC*Q2 ;
```

$$B2 := 1.253663354\ 10^{9} \tag{122}$$

```
> C2 := Totalabatementcosts_noinformation(p_a2) ;
```

$$C2 := 3.411714152\ 10^{7} \tag{123}$$

```
> W2 := Welfare(Q2, C2) ;
```

$$W2 := 1.219546212\ 10^{9} \tag{124}$$

```
> W1 - W2 ;
```

$$1.036445382\ 10^{10} \tag{125}$$

```
> %/%% ;
```

$$8.498615073 \tag{126}$$

```
> deltaW_2 := 100*(W2-W_nooffsets)/W_nooffsets ; #%
```

$$deltaW\_2 := -65.35380080 \tag{127}$$

```
> deltacosts_2 := 100*(C2-C_r_nooffsets)/C_r_nooffsets ; #%
```

$$deltacosts\_2 := -99.03076301 \tag{128}$$

```
> deltaB_2 := 100*(B2-B_nooffsets)/B_nooffsets ; #%
```

$$deltaB\_2 := -82.19228190 \tag{129}$$