Louvain School of Management
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Strategic emissions reductions in the supply chain based on the evolution of carbon regulations

A cost-minimization model under uncertainties

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Contents

1. Introduction

Climate change is one of the biggest challenges of our times (Zhou & Wang, 2016). Increased Greenhouse Gas (GHG) concentration, decreased air quality, rise of sea water level, and increase of global surface temperature are amongst the many disastrous consequences of climate change. According to the Intergovernmental Panel on Climate Change (ipcc), “climate change is already affecting every inhabited region across the globe, with human influence contributing to many observed changes in weather and climate extremes” (2021). On the 12th of December 2015, 196 Parties signed the Paris Agreement at COP 21 with the common objective to limit global warming to below 2°C and purse efforts to limit it to 1.5 °C compared to pre-industrial levels (United Nations, n.d.). Alongisde this international treaty, the European Union (EU) has set its own goals for climate action, with the implementation of the European Green Deal, of which the EU Taxonomy has drawn particular attention. The objective of these measures is to push the EU towards a 55% cut in emissions by 2030 and to reach carbon neutrality by 2050 (European Commission, n.d.). In order to reach these targets, the EU, through the European Climate Pact, wishes to “engage citizens and all parts of society in climate action” (European Commission, n.d.). Companies are crucial players in the transformation of markets and society (Schaltegger et al., 2016), which makes it essential for them to take part in global climate mitigation actions. In order to lead companies down the right path, different emission abatement mechanisms have been designed and their implementation is spreading across the globe. The most commonly used and more general forms of regulations are economic incentives such as Emissions Trading Systems, Carbon Taxes, Internal Carbon Pricing and Carbon Offsetting. These mechanisms rely on setting a price on carbon emissions, thereby increasing the companies’ costs, which, in turn, will incentivize them to lower their emissions as to maximize their profit. Unfortunately, most carbon prices today still remain below the USD 40-80/tCO2e range required to meet the objectives of the Paris Agreement, meaning that even higher prices will be needed over the next decade in order to reach this goal (World Bank, 2021). This upcoming increase in carbon prices will represent continuously larger constraints for companies who do not decide to rethink the way they conduct their business. Within the business operations of a company, the supply chain is known to be responsible for more than three quarters of the GHG emissions in many industries (Dasaklis & Pappis, 2013). Strategic investment decisions in the supply chains thus need to be taken today in order to decarbonize them and anticipate the future rises in carbon prices.

The aim of this thesis is to gain a solid understanding of the largest emission abatement mechanisms in place today, namely Emission Trading Systems (ETSs), Carbon Taxes, Internal Carbon Pricing (ICP) and Carbon offsetting and to analyze their evolution over the past decades, both in their characteristics and associated carbon prices. From this analysis and the insights gained from the literature review, predictions will be made on the likely future evolution of the carbon prices associated to various emissions abatement mechanisms. The objective behind this is to answer the following questions : *How can companies best deal with the uncertainties that arise from the predictions of the carbon prices evolution ?* and *How should companies use these predictions to invest strategically to decarbonize their supply chains today ?* The last point of research will be to observe whether companies react differently to various degrees of uncertainty of the carbon market evolution, depending on their level of aversion to the risk of high future carbon prices.

These questions could be tackled through many different angles. The first and commonly used tool would be to conduct interviews with companies that have experienced changes in their supply chain with the aim to reduce their emissions. However, working with them would give me an overview of these changes under past conditions and would not give me any insight on how companies should behave today as to face future challenges. Working on a practical case with a real company could have been interesting, but would have been better suited for a practical thesis linked to an internship. Indeed, I have chosen to conduct a theoretical thesis based on, in the first part, the review of existing literature on the various carbon abatement mechanisms and on the relationship between supply chains and climate change and, in the second part, the construction of optimization models that aim to answer the questions raised above. Focusing on the theoretical part first allows me to gain a deeper understanding of the mechanisms that I am working with and to create simplistic models that portray these characteristics well. The tool that I have chosen to answer the questions raised in this thesis is the use of stochastic optimization models. Cost-minimization is the key element to the majority of companies and, even if they decide to take voluntary climate actions, it will continue to remain central. Optimization is an efficient and reliable way of observing the outcomes of various scenarios and settings, and the use of stochastic programming will allow for the integration of the uncertainties linked to the evolution of carbon prices in the models. Moreover, optimizing a supply chain with the final objective to lower its emissions is a way to link the essence of both my masters degrees' majors : Supply Chain Management & Energy, Natural Resources and the Environment. Lastly, it should be noted that this thesis has been written considering that the reader is a co-student who has the same educational background as I do.

The thesis will be organized as follows : Firstly, an extensive review of the existing literature will be conducted and exposed in Section 2. The literature review will cover the history of carbon pricing (Section 2.1), four Carbon Pricing Instruments : Emissions Trading Systems (Section 2.2.1), Carbon Taxes (Section 2.2.2), Internal Carbon Pricing (Section 2.2.3) and Carbon Offsetting (Section 2.2.4) as well as the relationship between climate change and supply chain management with the introduction of Green Supply Chain Management (Section 0). Once an overview of the existing literature has been exposed, the methodology followed throughout the thesis will be outlined in Section 3 before moving on to the practical part. Section 4.1 holds an explanation of the fictive supply chain portrayed in the optimization models used as well as the assumptions made during their creation. The stochastics of the models and the multiple cases and scenarios that they lead to are laid out in Section 4.2 before further developing these models in Section 4.3. The results of the various optimization models will be exposed in Section 4.4 before being discussed in Section 5 and, finally, a conclusion will be drawn in Section 6.

2. Literature review

The market is made up of multiple actors that differ in market share and sustainability quality. The sustainability quality of a company refers to the extent to which they provide effective solutions to environmental and social problems (Schaltegger et al., 2016). Companies with a high market share can be thought of as *mass market players* and have significant power on the market, whereas companies with a smaller market share are *niche players* and have limited influence on the market. According to Hockerts & Wüstenhagen (2010), both small and big actors have a role to play in the transition of industries towards sustainable development. Indeed, as represented by Figure 1, niche players are challenged to grow and gain influence on the market in order to spread their sustainability quality, whereas mass market players need to transform their products and services so as to increase their sustainability quality (Schaltegger et al., 2016). It is important to note that "growth of sustainable companies is not the same as growth of the whole market" (Schaltegger et al., 2016). Indeed, economic growth is often seen as contradictory with sustainability but, as highlighted by Schaltegger et al., "growth of a sustainable company at the cost of unsustainable companies in a consolidated market leads to a structural change of the market towards sustainability".

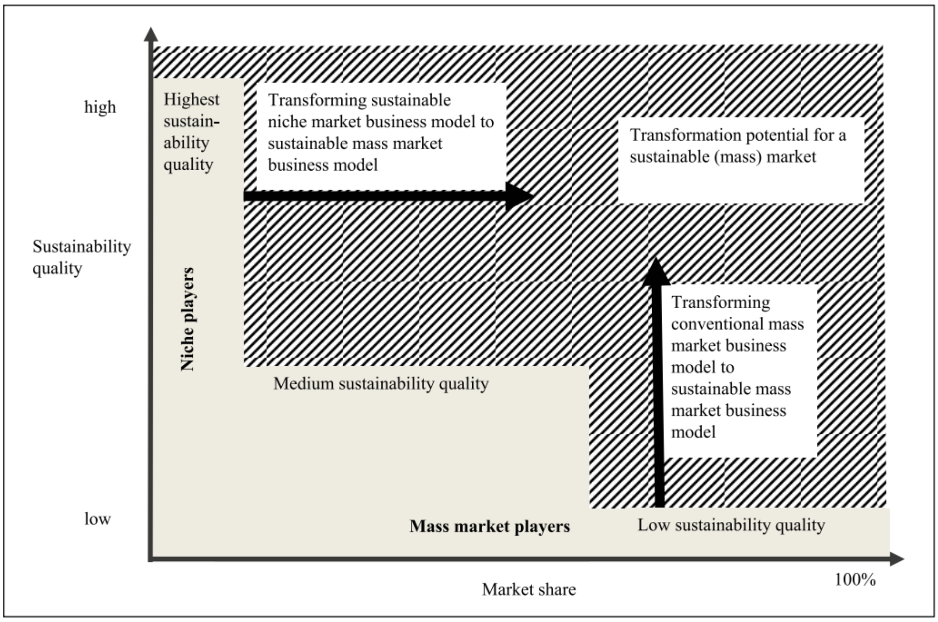


Figure 1 - Market transformation towards sustainable development (Schaltegger et al., 2016, p.269)

In order for companies to transition from low to high sustainability quality, their business model needs to be revised to ensure that their core-business is sustainability-oriented (Schaltegger et al., 2016). A business model is a concept that has been the topic of many research papers and therefore presents different definitions. According to Johnson et al. (2008), a business model "consists of four interlocking elements that, taken together, create and deliver value". These four elements include the *Customer value proposition* (how the company answers the customers' problem), *Profit formula* (how the company creates value for itself while providing value for the customer), *Key resources* (the assets required to deliver the value proposition) and *Key processes* (the operational and managerial processes required for the company to deliver value) (Johnson et al., 2008). The key resources and processes constitute the infrastructure through which the value is created (Schaltegger et al., 2016), and this infrastructure is directed by the supply chain. Sustainable supply chain management practices are thus a central aspect to the implementation of a sustainable business model.

According to Meager et al. (2020), one of the main drivers for the transition towards green supply chain management is the use of *environmental regulations*. The two major types of environmental regulations are *economic incentives* and *prescriptive regulations* (Kolstad, 2011). Prescriptive regulations can take many forms and can be thought of as being a guide to the steps that polluters must take to reduce their pollution level. The most common types of prescriptive regulations are *technology standards* and *performance standards* (Kolstad, 2011). Considering the fact that prescriptive regulations are usually industry-specfic, they are not well suited for the interest of this thesis, since the models to be built should be adaptable to different companies across industries. Economic incentives, however, have a much wider scope and are better suited to answer the questions raised here. There are several types of economics incentives, but they all aim to align public and private interests by "providing rewards for polluters to do what is perceived to be in the public interest" (Kolstad, 2011). There are many advantages to economic regulations. The first advantage is that the *equimarginal principle* will automatically hold for most types of regulations. This means that, for the same incentive, the marginal cost of emissions control will be equal amongst polluters, thereby equating the opportunity cost of emitting for all actors (Kolstad, 2011). The importance behind this is that regulations for which the equimarginal principle holds will result in lower overall costs of emissions control, which is beneficial for all actors (Kolstad, 2011). Another significant advantage of economic incentives lies in the spur for innovation. Indeed, actors are given the freedom to tackle emissions control in their preffered way and are therefore incited to innovate as to lower their emissions at the lowest possible cost (Kolstad, 2011). These innovations are then likely to spread across industries and result in overall emissions abatement. However, there is a significant disadvantage to economic regulations, which is the necessity to continuously adjust the level of the incentive over time (Kolstad, 2011). This phenomenon will be discussed to a large extent in the next Sections through an analysis of the evolution of carbon prices.

2.1 Carbon pricing

As far as economic incentives go, all regulations rely on carbon pricing instruments (CPIs). Pizarro (2020) defines a CPI as "a policy vehicle, implemented through a legal and institutional infrastructure, that can deliver a price on carbon emissions on specific sectors or entities". These instruments can either be *explicit* or *implicit* (World Bank, 2021). "Explicit carbon pricing policies are enacted by a government mandate and impose a price based on carbon content" (World Bank, 2021). These policies give freedom to the polluters as to how they wish to tackle emissions abatement, thereby promoting cost-effectiveness, and usually take the form of a carbon tax or an Emissions Trading System (World Bank, 2021). An implicit carbon price, however, is derived by "calculating the equivalent monetary value per tonne of carbon associated with a given policy instrument" and is used "to compare the stringency of different mitigation policies, like performance/efficiency standards […] or regulations that mandate the use of specific low- or zero-carbon technologies" (World Bank, 2021). Implicit pricing policies are thus mostly used for prescriptive regulations, which, as previously mentionned, are not aligned with the interest of this thesis, and will therefore not be considered.

CPIs are used by many governments as a tool to reach their climate objectives. Curently, 29 countries have adopted net-zero commitments, of which 22 already have carbon prices in place (World Bank, 2021). However, the majority of carbon prices in use today are still too low to meet the 2°C limit of the Paris Agreement. Indeed, the required range of carbon prices that will guarantee the reach of this goal is USD 40-80/tCO2e, but "only 3.76% of global emissions are covered by a carbon price at and above this range", meaning that "even higher prices will be needed over the next decade to reach the 1.5°C target" (World Bank, 2021; Carbon Pricing Leadership Coalition & World Bank, 2017). The carbon prices are volatile and, although they differ depending on the CPI design in place, they also vary due to external parameters. This will be discussed further in Section 3.2.1. The design of CPIs has evolved over the years and will keep adapting in the future, based on the strengths and weaknesses of the tools in use today. These changes have also been influenced by the evolution of the emissions allocation methods. Determining who bears the responsibility of climate change mitigation is a never ending discussion undertaken by many philosophers, for which a consensus has not yet been reached, and probably never will be. However, it has not stopped the development of multiple allocation methods from occuring. According to Zhou & Wang (2016), there are several levels at which the allocation of CO2 emissions can be performed : between countries, between domestic regions or even between firms in a regulatory system. Within these levels, the issue of selecting the allocation method to be followed persists. In their paper on "*Carbon dioxide emissions allocation – A review"*, Zhou & Wang (2016) highlight four categories of approaches. These four approaches either follow the *fairness principle,* which aims to allocate emissions according to distributive justice, or the *efficiency principle*, which has the objective to lead to an economically efficient allocation of emissions (Zhou & Wang, 2016). The fairness principle further declines into different perspectives such as *grandfathering*, *egalitarianism*, *polluter pays*, etc., which all refer to different emission allocation methods (Zhou & Wang, 2016). Grandfathering is a commonly used allocation method according to which allowances are distributed based on prior allocation, thereby giving preferential treatment to existing entities. The choice of allocation method will have different welfare implications, each having their strengths and weaknesses and leading to the development of different CPIs.

As previously mentionned, Emissions Trading Systems and carbon taxes are the most common types of explicit CPIs (World Bank, 2021). On top of the differences that arise from the choice of allocation method, as explained above, there is a range of macro-design choices that changes the nature, object, outcome and viability of the instrument (Pizarro, 2020). A common example to illustrate this statement is the difference in outcome of a tax on fuel versus a tax on emissions, even though they are both taxes. According the Pizarro (2020) the five features that change the macro-design of a CPI are as follows : *choice between tax and ETS, choice of emissions or fuels as the base, choice of CO2 or GHG as the contaminant, what to do with the revenue* and *whether to have complementary market features such as offsets and emissions trading in secondary markets*. The result of these choices will "have considerable economic, institutional and, above all, political economy consequences" (Pizarro, 2020). As of February 2022, 65 carbon pricing initiatives have been implemented, covering 45 national and 34 subnational jurisdictions (Carbon Pricing Dashboard, 2021). Although these jurisdictions all use instruments based on carbon pricing, their CPI differs in its macro-design as to adapt to its location. Indeed, governments must conduct the choice of CPI to be implemented based on national circumstances and political realities, where the CPI's objectives are aligned with the national economic priorities and institutional capacities of the jurisdiction in question (Carbon Border Adjustment Mechanism, 2021). The following Sections will outline multiple CPIs so as to gain a deeper understanding of their implications, strengths and weaknesses.

2.2 Emissions abatement mechanisms

Under the Kyoto Protocol, signed in 1997, the participating countries were required to reduce their GHG emissions by 5.2% below 1990 levels (European Commission, Carbon Border Adjustment Mechanism, 2021). This objective was the start of the use of emissions abatement mechanisms. To reach it, the signatory countries could decide between conducting domestic emission reductions or take part in one of three abatement mechanisms: *International Emissions Trading (IET)*, *Joint Implementation (JI)* or *Clean Development Mechanism (CDM)* (European Commission, Carbon Border Adjustment Mechanism, 2021). The IET system is an international ETS with the aim of achieving emission reduction at the lowest cost. However, the differences in national policies between countries involved in the IET prevented cost minimization from taking place, making this tool inefficient (European Commission, Carbon Border Adjustment Mechanism, 2021). The JI and CDM are both offset-based mechanisms where countries could participate in and finance low-carbon projects in developing countries and obtain emission credits in return, thereby allowing them to deduce the emission reductions performed elsewhere from their own pollution levels (European Commission, Carbon Border Adjustment Mechanism, 2021). These three mechanisms, each having their own failures and successes, are the first CPIs to have been implemented.

A significant difference between the outcomes of the Kyoto Protocol and the Paris Agreement lies in the obligations of the participating countries. Indeed, under the Paris Agreement, all countries are obliged to submit Nationally Determined Contributions whereas only developed countries were binded to do so under the Kyoto Protocol (Parker, 2019). The signatories are however still allowed to decide how to pursue their contributions between a range of domestic measures such as direct emission reductions, offset programs or energy efficiency improvements, for example (Parker, 2019). Moreover, as recognized by Article 6.2 of the Paris Agreement, “parties may, ‘on a voluntary basis’, pursue cooperation to use Internationally Transferred Mitigation Outcomes to implement their Nationally Determined Contributions” (Parker, 2019). This evolution in the scope of emission abatement obligations justifies the need for the implementation of additional CPIs. To ensure their adaptation to new circumstances, they are implemented based on past experiences and knowledge from various studies published by organizations such as the World Bank Group and the Organisation for Economic Co-operation and Development (OECD), aiming to help governments and businesses develop efficient and cost effective tools (Parker, 2019).

2.2.1 Emissions Trading Systems

Emission Trading Systems (ETSs) are one of the most commonly used CPIs in the world. Under this instrument, entities can comply with their abatement objectives either by performing an internal emissions reduction or by acquiring emission units on the carbon market, or both. These emission units can then be traded between market participants, thereby allowing polluters to buy and sell the right to pollute and making this a market-based approach (Kolstad, 2011). The trade-off between the two compliance alternatives depends on their relative costs, considering that companies aim to reach their target while minimizing their costs (Carbon Pricing Dashboard, 2021).

The two main types of ETSs are *cap-and-trade*, also called *marketable permit system*, and *baseline-and-credit* (Kolstad, 2011; Carbon Pricing Dashboard, 2021). In a cap-and-trade system, which is the most commonly used today, a limit, or *cap*, is set on the maximum level of emissions allowed within the ETS. These allowances are then distributed amongst the participating entities, either freely or through an auction (Carbon Pricing Dashboard, 2021). In a baseline-and-credit system, however, the process is reversed. Indeed, emission allowances are defined for each entity and the sum of these allowances forms the cap (Carbon Pricing Dashboard, 2021). This is the case for the recently launched Chinese ETS, where the cap is said to be set “bottom-up” (icap, 2021). Both systems have the advantage of being cost-effective due to the fact that “when firms trade pollution permits, the price of the permit that will be determined by the permit market sends the same signal to all polluters regarding the opportunity cost of emitting” (Kolstad, 2011). Another advantage of these systems is that they incentivize innovation (Kolstad, 2011) both in the entities that are subject to the ETS and on a national scale through the governments which use the funds to invest in low-carbon technologies and projects.

Currently, there are 10 national or regional ETSs that have been fully implemented (Carbon Pricing Dashboard, 2021), some of which will be discussed in more details in this Section. Each ETS has its own specifications and therefore results in slightly different outcomes. Since the cap-and-trade system is the most currently used ETS design, it will be explored in more details through the analysis of the EU ETS.

Implemented in 2005, the EU ETS was the first major carbon market in the world, aiming to steer the EU towards compliance of its Climate Goals under the European Green Deal (European Commission, EU Emissions Trading System (EU ETS), 2021). The EU ETS is made up of four phases, with the fourth phase having started in 2021 and ending in 2030, and covering about 40% of the EU’s GHG emissions (European Commission, EU Emissions Trading System (EU ETS), 2021). The EU ETS is designed as a cap-and-trade system with a an annual decrease in the cap of 2.2% since 2021, thereby ensuring a continuous decrease of emissions (European Commission, General Guidance to the allocation methodology, 2019). In the EU ETS, the emission allowances that constitute the cap are distributed primarily through auctioning. Indeed, it is “based on a Union-wide harmonised allocation method in which auctioning should be the basic principle for allocation, as it is the simplest and generally considered to be the most economically efficient system” (European Commission, General Guidance to the allocation methodology, 2019). However, some allowances remain distributed under free allocation. The amount of allowances distributed freely has significantly decreased between phase 3 and 4, with a 57% share of total allowances to be auctioned, leaving only 43% to free distribution (European Commission, General Guidance to the allocation methodology, 2019). The lower share of allowances “will be used in a more focused approach to avoid carbon leakage” (European Commission, General Guidance to the allocation methodology, 2019).

Carbon leakage is a phenomenon that occurs when countries with strict regulations on emissions transfer their production to countries without such regulations, thereby avoiding the costs of emissions abatement or taxes and simply relocating the emissions elsewhere (Saevarsdottir et al., 2019). Many CPIs are thus accompagnied by strategies to avoid carbon leakage. In the case of the EU ETS, "industrial installations considered to be at significant risk of carbon leakage receive special treatment to support their competitiveness" and are assigned a higher share of free allowances (European Commission, Carbon Leakage, 2019). The 4th phase of the ETS, although aiming to phase out of free allocations towards a complete auctioning of allowances by 2030, has seen introduced an act dedicated to the avoidance of carbon leakage (European Commission, General Guidance to the allocation methodology, 2019).

"Auctioning is the most transparent method for allocating emission allowances and puts into pratice the principle that the polluter should pay" (European Commission, Auctioning, 2021). The *polluter pays* principle, which was briefly introduced in Section 2.1, is an allocation criteria that follows the fairness principle and uses the CO2 indicator to distribute the emissions reduction responsibility relative to the cumulated emissions (Zhou & Wang, 2016). The auctioninng takes place on a common platform where the member states can auction their allowances under the ETS Directive and the Auctioning Regulation (European Commission, EU Emissions Trading System (EU ETS), 2021). The ETS Directive states that the governments must invest at least 50% of the auctioning revenues in climate and energy-related purposes and report on these expenses annually (European Commission, EU Emissions Trading System (EU ETS), 2021). This highlights the spur for innovation incentivized through the use of economic regulations mentionned by Kolstad (2011). Although auctioning is the general rule, a share of total allowances, as mentionned above, remains allocated through free distribution. Since the start of phase 3 (in 2013), the free allocation methodology consists of a benchmarking technique based on the GHG emission intensity, which has the advantage that "all installations receive the same number of free allowance per tonne of product produced" (European Commission, Update of benchmark values for the years 2021 - 2025 of phase 4 of the EU ETS, 2021). In contrast to the *polluter pays* criterion which follows the fairness principle, the *emission intensity* criteria follows the efficiency principle (Zhou & Wang, 2016). The EU ETS thereby regroups both fairness and efficiency principles in the same CPI by having a combination of auctionning and free allocation of the emissions.

As highlighted by Figure 2, there are currently ten national or international ETSs implemented around the world (Carbon Pricing Dashboard, 2021). The EU ETS was the first to be implemented in 2005 and was the first major carbon market in the world. Today, it is being slowly overtaken by the Chinese National ETS, launched only in 2021, and covering more than four billion tCO2 emissions, thereby accounting for about 40% of national carbon emissions (World Bank, 2021 ; icap, 2021). In between the implementation of these two major ETSs, other countries also joined the trend of using an ETS as their CPI. Table 1 outlines the major structural differences and similarities between the EU ETS, the California Cap and Trade program (California CaT), the New Zealand ETS, the Regional Greenhouse Gas Initiative (RGGI) in the United States, the Chinese ETS and the Kazakhstan ETS.

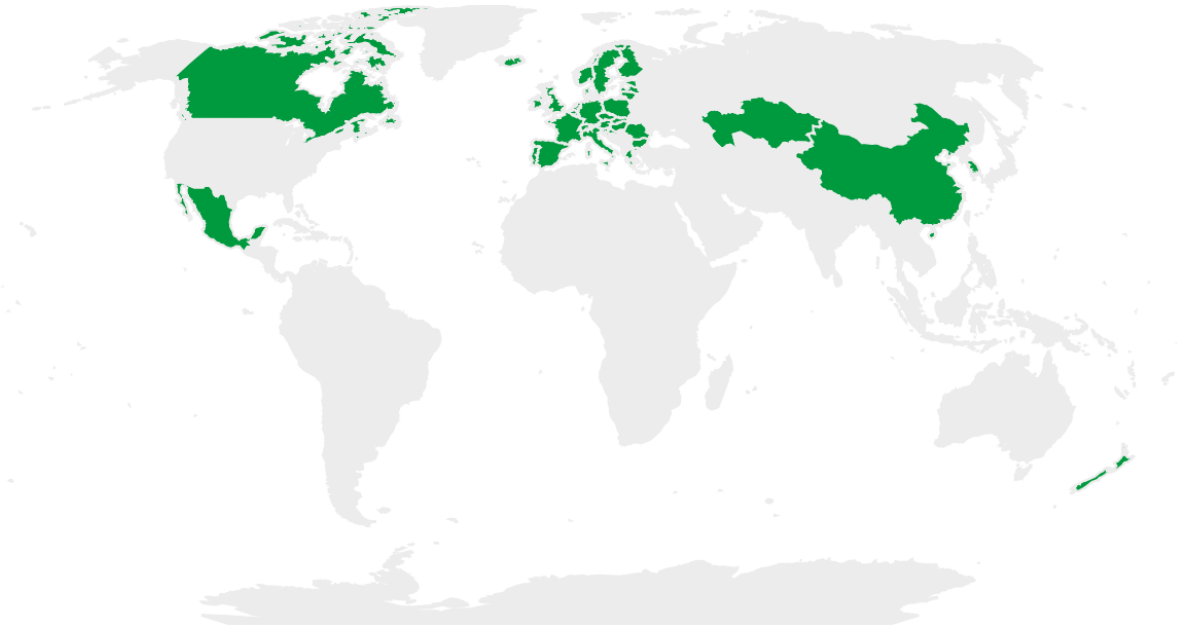


Figure 2 - Map of currently implemented ETSs (Carbon Pricing Dashboard, 2021, https://carbonpricingdashboard.worldbank.org/map_data1)

Table 1 - Comparison of ETSs currently implemented (Parker, 2019; icap, 2021; World Bank, 2021)

	EU ETS	**California CaT**	**New Zealand ETS**	**RGGI**	**Chinese ETS**	**Kazakhstan ETS**
Implementation year	Pilot : 2005 Final : 2008	2012	2008	First compliance period : 2009-2011	2021	Pilot : 2013 Final : 2014

ETS design	Cap-and-trade	Cap-and-trade	Cap-and-trade	Cap-and-trade – Reduction target or cap set by each member	Baseline-and-credit	Cap-and-trade
Allowances allocation method	Phase out of free distribution towards auctioning	Free distribiuion & auctioning	Free distribution	Auctioning of all allowances	Free distribution	Free distribution
Use of international units	No anticipated use in phase 4	Not permitted (may change)	Not permitted	Not permitted	Not implemented yet	Curently not permitted, future use under consideration
Use of offsetting mechanisms	Insignificant role of offsetting mechanisms	Permitted – subject to a limit of 4% of total emissions	Permitted with no quantitative limit	Permitted - subject to quantitative limit of 3.3%	Permitted – subject to quantitative limit of 5%	Under consideration, currently generally prohibited

The EU has been a model for the implementation of ETSs in other countries (Parker, 2019). Switzerland, for example, who was one of the first countries to launch their ETS after the EU, based its model largely on the existing EU ETS with very few differences in their design. In 2021, they eventually linked for the fourth phase of the EU ETS (Parker, 2019). The allocation method of the allowances is one of the major differences between all the ETSs. Several systems still largely use free distribution as an allocation method, although not judged cost-effective by the EU. Kazakhstan, for instance, allocates 100% of its allowances freely with the use of grandfathering and benchmarking methodology, thereby following the fairness and the efficiency principles, respectively (Parker, 2019). On the other hand, the RGGI system, which was the first sub-national ETS implemented, uses solely auctioning for the allocation of allowances, and is currently the only system to do so (Parker, 2019). Finally, in California, the allowanced are allocated both through free distribution and through auctioning, depending on the type of company (Parker, 2019).

Another major difference lies within the coverage of the ETSs. Usually, the coverage of an ETS tends to widen over the years. However, a few exceptions to this rule have been experienced, such as the decreased scope of the inclusion of aviation in the EU ETS (European Commission, EU Emissions Trading System (EU ETS), 2021). “Initial rules applied to all flights to or from a member state, but application was quickly limited to wholly intra-member flights" (Parker, 2019). The energy sector is the most commonly covered sector in ETSs along with industrial processes (European Commission, EU Emissions Trading System (EU ETS), 2021; Parker, 2019). New Zealand began by covering the forestry sector before adding on the energy, industrial processing and fuel sectors (Parker, 2019). Large differences in sectors and GHG coverage remain between the ETSs, which can be explained by the need for CPIs to reflect the political realities of each jurisdiction (European Commission, Carbon Border Adjustment Mechanism, 2021).

The use of international credits also varies significantly between the ETSs mentionned in this Section. This refers to the use of Internationally Transferred Mitigation Outcomes for countries to complete their Nationally Determined Contributions. The use of international credits presents some challenges. The first challenge is the difficulty in assessing the environmental integrity of credits purchased elsewhere (Parker, 2019). Another challenge, which has largely impacted the EU and New Zealand, is that the use of international credits tends to drive down the price of carbon units on the market. Indeed, it can lead to an oversupply of carbon units, thereby reducing their monetary value and, in turn, the incentive for firms to lower their emissions (European Commission, Market Stability Reserve, 2021). In the EU, the surplus of allowances reached 2.1 billion in 2013 (European Commission, Market Stability Reserve, 2021). To counteract this effect, the European Commission implemented two strategies. *Back-loading* is a short-term measure that entered into force in 2014 and that postponed the auctioning of 900 million allowances until 2019. This measure allowed the rebalancing of supply and demand and reduced price volatility (European Commission, Market Stability Reserve, 2021). The *market stability reserve* is another measure introduced by the European Commission in 2019 that tackles a long-term price regulation of the system. This measure adapts the quantity of allowances to be allocated by acting as a reserve which can take-in or give-out allowances, depending on the situation (European Commission, Market Stability Reserve, 2021). An overall tendency of phasing out of international credits use can be observed, most likely driven by the negative experience of New Zealand and the EU (Parker, 2019).

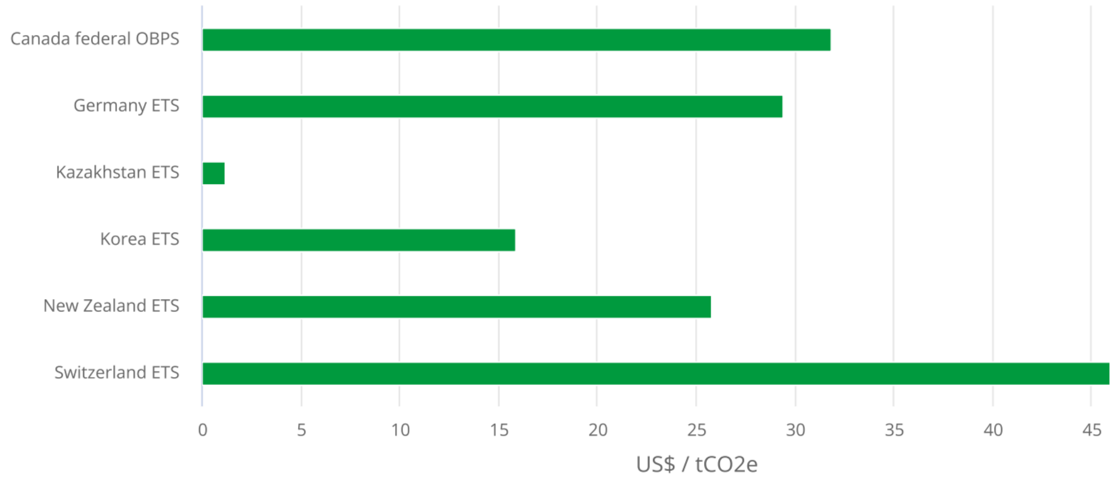


Figure 3 - Carbon prices in ETSs (Carbon Pricing Dashboard, 2021, https://carbonpricingdashboard.worldbank.org/map_data)

Figure 3 portrays the prices for carbon units in multiple ETSs currently implemented. It is clear that the prices vary immensely and are mostly lower than the 40 – 80 USD/tCO2 range required to meet the climate goals of the Paris Agreement (World Bank, 2021). Currently, only the EU and Switzerland have carbon prices in this range, with revenues generated amounting to 22.548m USD and 8m USD in 2020, respectively (World Bank, 2021).

In Section 4.2, a forecast will be performed based on historical data of two ETSs. The collection of this data shows that the carbon prices evolve continuously over time. This constant evolution represents the main disadvantage of economic incentives, according to Kolstad (2011). The fact that there are many uncertainties linked to the climate problem and how it should be managed calls for regular adaptation of the ETS, both in the level of the fee and in the number of marketable permits, as information becomes available (Kolstad, 2011). Knowing that some ETSs in place today have a compliance region that includes several countries, the frequent changes that are necessary to adapt to climate change may not be easy to make, which presents a significant disadvantage of economic incentives.

2.2.2 Carbon taxes

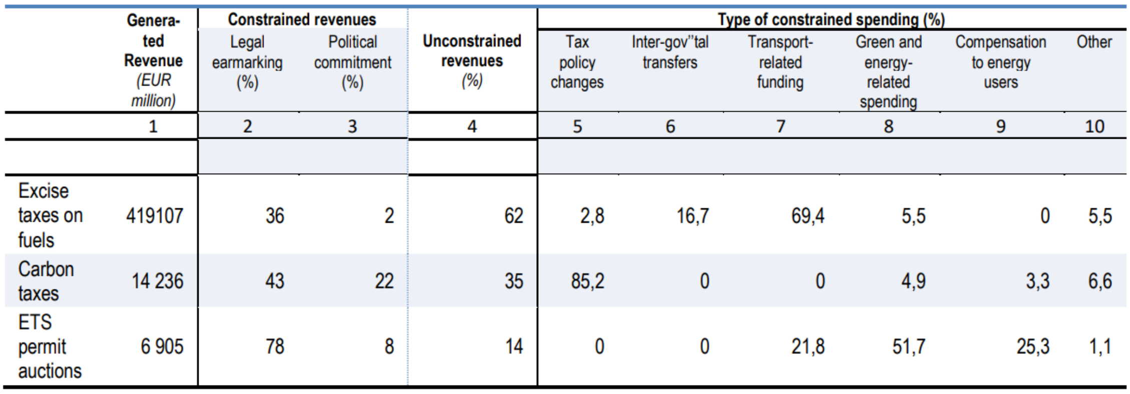
When the Kyoto Protocol was signed in 1997, it was a strong belief that “well-designed environmental taxes would be effective tools in solving the climate problem” (Nar, 2020), and this belief persisted under the Paris Agreement (Metcalf, 2019). Carbon taxes were implemented as to incentivize the choice of greener energy sources, increase energy efficiency and lower the consumption of fossil fuels, and do so cost-effectively (Nar, 2020).

Pollution, no matter where it occurs on the planet, affects climate change on a global scale (Kolstad, 2011). The cost of polluting can therefore be thought of as a societal cost, as it is shared between all individuals. This societal cost is a negative externality that, traditionally, is not reflected in the market price of goods or services (Marten & van Dender, 2019). Therefore, the producers do not take it into account when deciding on their production level and the consumers do not consider it in their choice of consumption level, which leads to inefficient levels of production and consumption (Marten & van Dender, 2019). Environmental taxes allow for the societal cost of polluting to be included in the market price by internalizing it, thereby leading to more effective consumption and production levels (Nar, 2020). The cost of polluting is commonly used to set the tax rate. Indeed, the tax rate will be fixed equal to the estimated benefits of reducing GHG emissions by a certain amount of CO2e, usually 1 ton (Nar, 2020).

A carbon tax, in the same way as an ETS, is an explicit CPI (World Bank, 2021). It is “a regulation tool that orients financial and social policies in matters of investment incentives, redistribution of wealth, securing economic stability and stopping unwanted financial activities” (Nar, 2020). A major difference between the use of a carbon tax and an ETS is that carbon taxes do not have a cap on emissions and therefore do not have a predefined emissions reduction outcome (Carbon Pricing Dashboard, 2021; Kolstad, 2011). A common outcome, however, of ETSs (under auctioning) and carbon taxes is the creation of national or sub-national revenue. This tax revenue arises from the introduction of the societal cost of pollution into the market price, as discussed above. However, the tax creates a decline in consumer and producer benefits as, “part of the benefits that accrued to them before the tax are transformed into tax revenue” and are no longer collected by the producer (Marten & van Dender, 2019). This is considering that pollution control is not included in consumer and producer benefits. The utilization of this tax revenue will determine the effectiveness of the carbon tax in reducing GHG emissions. The share of tax revenue that entities are obliged to spend on environmental-related projects or investments depends on each jurisdiction. For example, Switzerland has to spend a third of their carbon tax revenue on energy efficiency measures, which was equivalent to EUR 450 million in 2018 and increased to EUR 826 million in 2021 (Marten & van Dender, 2019; World Bank, 2021). This is called a *constraint on revenue* and goes into much more details that will not be discussed here.

Constraints on revenues are very common and vary depending on the CPI in use (Marten & van Dender, 2019). In their study of 40 member countries of the Organization for Economic Co-operation and Develomment (OECD), Marten & van Dender (2019) found that 60% of the countries where a carbon tax is implemented have constraints on their revenues, as opposed to 80% for the use of ETSs. Table 2 below outlines the share of constrained and unconstrained revenue as well as the share exposed to each type of constraint, for different CPIs. From this table, it is clear that revenues from carbon taxes are mostly subject to constraints in *Tax policy changes*. This means that this share of tax revenues is to be used to support tax cuts, rebates, tax-free threshold increases, etc. (Marten & van Dender, 2019). One of the most criticized aspects of carbon taxes is the unclear and ineffective use of their generated revenue. Many studies claim that carbon taxes play no role in the reduction of GHG emissions due to the fact that tax revenues are simply used to feed the general budget and not dedicated to specific environmental projects (Nar, 2020). Constraints on carbon tax revenues are therefore a critical tool for an effective use of carbon taxes to reduce emission levels and should continue to be enforced.

Table 2 - Constrained and unconstrained revenue for multiple CPIs (Marten & van Dender, 2019, p.16)



	Genera-ted Revenue *(EUR million)*	**Constrained revenues**		**Unconstrained revenues** *(%)*	**Type of constrained spending (%)**					
		Legal earmarking (%)	Political commitment (%)		Tax policy changes	Inter-gov"tal transfers	Transport-related funding	Green and energy-related spending	Compensation to energy users	Other
	1	2	3	4	5	6	7	8	9	10
Excise taxes on fuels	419107	36	2	62	2,8	16,7	69,4	5,5	0	5,5
Carbon taxes	14 236	43	22	35	85,2	0	0	4,9	3,3	6,6
ETS permit auctions	6 905	78	8	14	0	0	21,8	51,7	25,3	1,1

Introducing a carbon tax will have significant effects on the economy (Gu & Wang, 2019) and should therefore, once again, be adapted to the national economic prioritities and institutional capacities of each jurisdiction in order to avoid negative economic consequences (European Commission, Carbon Border Adjustment Mechanism, 2021). This adaptation can be observed in the significant differences in carbon tax rates between jurisdictions. According to Gu & Wang (2019), carbon taxes may cause economic losses, especially in developing countries, which will therefore tend to have lower carbon tax rates.

A way to lower this economic loss while further reducing GHG emissions is to invest the tax revenue into innovation through the imposition of a revenue constraint (Gu & Wang, 2019).

Figure 4 exhibits the 35 national and subnational jurisdictions in which a carbon tax is implemented today. Together, they cover 2.99 Gt of CO2e, which represents 5% of global GHG emissions (Carbon Pricing Dashboard, 2021). The first countries to implement a carbon tax were Poland and Finland in 1990 followed shortly after by Norway in 1991 and then Denmark in 1992. The most recent carbon taxes were introduced in Taumaulipas (a Mexican state), Luxemburg and the Netherlands in 2021 (Carbon Pricing Dashboard, 2021; World Bank, 2021). The major differences between the carbon tax regimes implemented in the 35 jurisdictions are the coverage and exemptions, the payment frequence, the use of a complementary CPI and the tax rate.

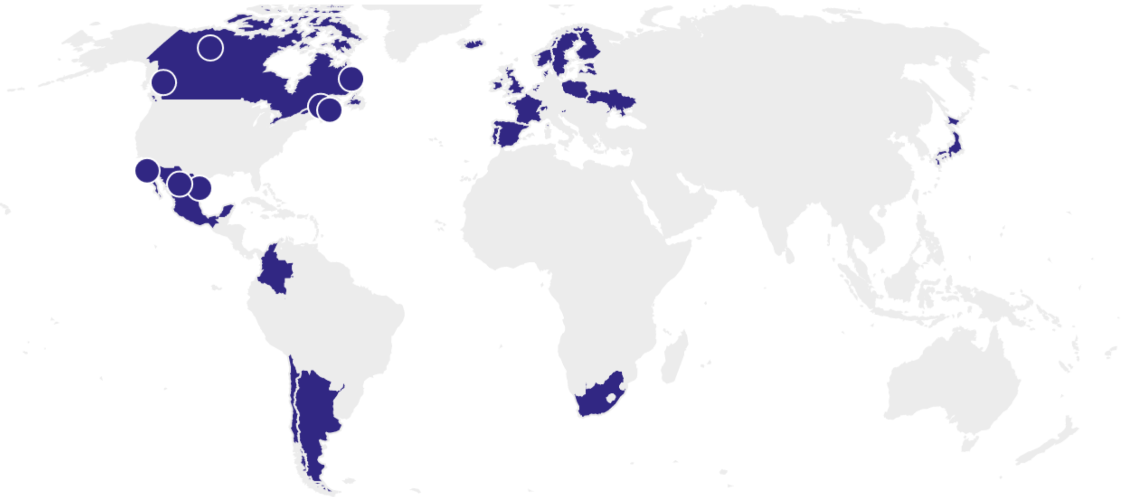


Figure 4 - Map of currently implemented carbon taxes (Carbon Pricing Dashboard, 2021, https://carbonpricingdashboard.worldbank.org/map_data

Table 3 below presents these differences for several jurisdictions.

Table 3 -Comparison of carbon taxes currently implemented (Carbon Pricing Dashboard, 2021; World Bank, 2021

	Poland	**Norway**	**Tamaulipas**	**Luxemburg**	**Colombia**
Implementation year	1990	1991	2021	2021	2017
National / subnational	National	National	Subnational	National	Subnational

Complementary CPI	EU ETS	EU ETS	Pilot national ETS	EU ETS	/
Coverage	GHG emissions from all sectors, all fossil fuels and other fuels leading to GHG emissions	GHG emissions from all sectors	GHG emissions from all sectors	Fossil fuels for transportation and heating	GHG emissions from all sectors
Exemptions	Operators covered by EU ETS	Operators covered by EU ETS (with exceptions)	Facilities that emit less than 25 tCO2e of GHG monthly	Fossil fuels for electricity generation	Carbon neutral certified gossil fuel consumers and natural gas consumers not in the petrochemical and refinery sectors
Payment frequence	Annual	Monthly	Monthly	Monthly	Bimonthly
Tax rate	USD 0.08/tCO2e	USD 4/tCO2e – USD 69/tCO2e	USD 13/tCO2e	USD 23.49/tCO2e – USD 40.12/tCO2e	USD 5/tCO2e

It can be seen in Table 3 that most jurisdictions have a carbon tax coverage of GHG emissions from all sectors, except Luxemburg that, already covered by the EU ETS, only aims at reducing GHG emissions from the transport and heating industries that are not covered by the ETS. The exemptions to the carbon tax vary depending on the jurisdiction and its economic activities but usually exist due to competitivity issues. As opposed to the other systems, the exemptions under the Tamaulipas regime are not based on particular activities but on an emissions quota of 25 tCO2e under which entities are not subject to the carbon tax (Carbon Pricing Dashboard, 2021). In most jurisdictions, operators that are covered by another CPI are not subject to the carbon tax. However, in Norway, some of the operators covered by the EU ETS, such as offshore oil producers, are also covered by the carbon tax. These exceptions account for an overlap of 48% of the emissions covered by the tax rate that are also covered by the EU ETS (Carbon Pricing Dashboard, 2021). This overlap creates an even stronger incentive for these operators to reduce their GHG emissions.

Table 3 also outlines the significant tax rates differences between the jurisdictions. Currently, Sweden presents the highest carbon tax rate of USD 137/tCO2e and Poland the lowest carbon tax rate of USD 0.08/tCO2e (World Bank, 2021). As previously mentioned, the carbon prices must be in the range of USD 40-80/tCO2e in order to reach the 1.5°C temperature goal of the Paris Agreement (Carbon Pricing Leadership Coalition & World Bank, 2017). “An analysis of the 48 new and updated NDCs in February 2021 found that implementation of current commitments would only lead to a 0.5% reduction in global emissions by 2030 compared to 2010 level, far short of the 45% reductions needed to limit global temperature increase to 1.5°C compared to pre-industrial levels (Energy & Climate Intelligence Unit, 2021). To reach the climate goals, carbon prices will thus need to be increased. However, if some jurisdictions increase their price too much in comparison to others, it could lead to carbon leakage (Nar, 2020), which does not help towards completion of the climate goals. In order to achieve the initial expectations of carbon taxes, their efficiency will need to increase significantly. According to Nar (2020), the effectiveness of carbon tax in lowering GHG emissions remains controversial. Indeed, different studies consider them to be effective or partially effective while others deny the causal relationship between the implementation of a carbon tax and the reduction of GHG emissions (Nar, 2020). To increase the effectiveness of carbon pricing, carbon tax regimes should be complemented with other CPIs such as ETSs, as is the case in many jurisdictions today (Carbon Pricing Dashboard, 2021; Nar, 2020).

2.2.3 Internal Carbon Pricing

For companies to continue to grow sustainably, they have to recognize the ongoing and upcoming changes in policy, social norms and technology. Carbon pricing is one of the most prominent areas in which these changes will occur (Fan et al., 2021). Climate change will undeniably change the way that companies operate in the future, and investors and financial regulators are pressuring companies to disclose their risk mitigation strategies and policies implemented as to face the upcoming challenges (Bento et al., 2021). A way to incorporate the future challenges of climate change into a company’s decision-making process is through the implementation of Internal Carbon Pricing (ICP), a carbon pricing instrument that is internal to the companies and not regulated by the authorities. This voluntary pricing instrument aims to guide the investment decisions of companies towards low carbon investments while promoting efficient business operations (World Bank, 2021; Carbon Pricing Dashboard, 2021). This is achieved through the use of an internal charge on carbon emissions from assets and investment projects. The implementation of ICP is recommended by corporate climate governance initiatives such as the Task Force on Climate-related Financial Disclosures (TCFD) as one of the most useful tools for companies to disclose their climate-related risks and opportunities (TCFD, 2020). In addition to the prioritization of low-carbon investments, the use of ICP also raises funds that the company can then invest in sustainable projects (World Bank, 2021).

The most common form of ICP is called *shadow carbon pricing* and "sets a hypothetical carbon cost to each ton of emissions to identify climate risks and opportunities" (World Bank, 2021). Alternatively, *implicit carbon pricing* is another form of ICP where the carbon price is based on the "capital investments needed to achieve certain climate target ex-post and uses this value as a benchmark to guide future investments" (World Bank, 2021). This implicit carbon price is often based on the cost of offsetting the emissions of a particular project or investment (World Bank, 2021).

According to the World Bank (2021), the number of companies disclosing their use of ICP has increased significantly over the past year. Today, "nearly half of the largest 500 companies in the world by market value already have an internal carbon price or intend to adopt one" (World Bank, 2021). As discussed in the introduction of Section 2, mass market players have significant power over the market, meaning that their use of ICP will most likely influence smaller actors to use it too, thereby driving the market towards sustainable investment decisions (Schaltegger et al., 2016). The use of ICP is constantly evolving, and instead of simply looking to evaluate the risks of mandatory pricing instruments, businesses are looking for new ways to use ICP as to align their investments and business operations with their climate objectives. "For instance, major banking institutions are using carbon pricing approaches to review credit applications and assess their own portfolio footprint, while major indices are accounting for climate risks and climate policy including carbon pricing" (Carbon Pricing Leadership Coalition, Carbon Pricing in Action, 2021). Indeed, many companies are starting to push the use of ICP further and using it as a tool to evaluate the impact of potential future CPIs on their operations "and to explore cost savings and revenu opportunities through innovation" (Carbon Pricing Dashboard, 2021). ICP is thus an instrument that helps companies adapt to the potential evolution of carbon pricing by taking it into account in their decision-making process. ICP is used in different types of entities, ranging from corporate applications for a shift to low-carbon business models, to financial institutions through portfolio assessments, or even governments in policy design and project approvals (Carbon Pricing Dashboard, 2021). The sectors in which the largest implementation of ICP has been recognized are the energy, materials and financial industries (Fan et al., 2021). The internal carbon price used varies greatly depending on the sector and on the region. Figure 5 shows the distribution of internal carbon prices across sectors and for all regions of the world. It can be clearly seen that, in the same way as for ETSs and carbon taxes, most prices are much lower than the required range to meet the climate goals of the Paris Agreement. In fact, according to the World Bank (2021), the median price for shadow carbon pricing is USD 28/tCO2e. The range highlighted on Figure 5 has been determined by the Carbon Pricing Corridor's initiative, an initiative that "aims to provide a valuable benchmark for business and investors who are seeking to make strategic decisions consistent with a low-carbon economy, but who struggle with a lack of information about the risks and opportunities involved in the transition" (CDP, n.d.). Companies using ICP as a strategy to anticipate increases in carbon prices from mandatory CPIs should implement internal prices in accordance with the Carbon Pricing Corridor's initiative. If lower prices are set, the companies will not take the adequate investment decisions to minimize their climate-related

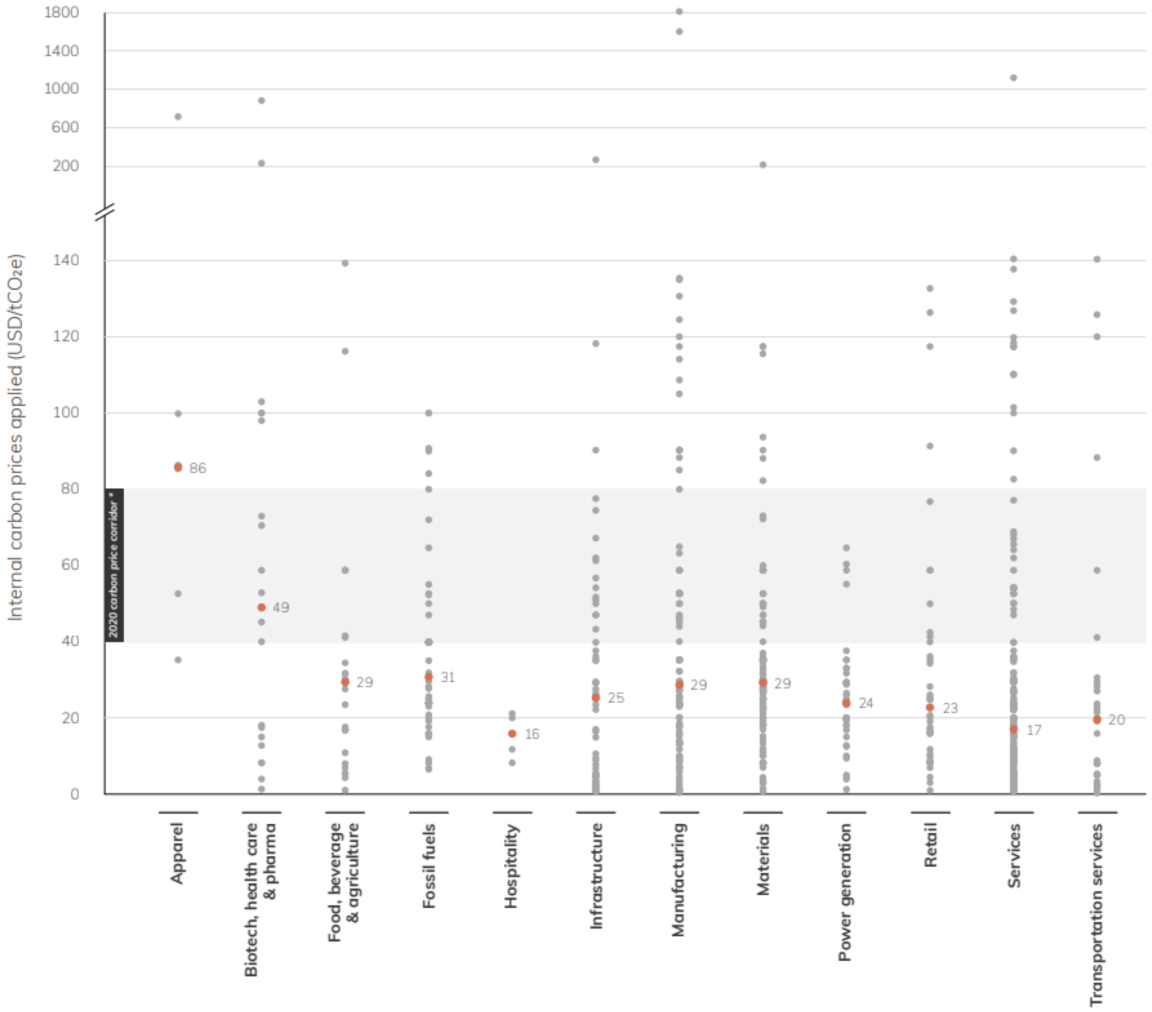


Figure 5 - Internal carbon prices across industries (World Bank, 2021, p.57)

risks. Certain companies are more affected by increases in the carbon price. It is the case for companies with long lasting assets such as heavy industries or energy companies, which have a higher incentive to set higher internal prices as to mitigate their risks (Bento et al., 2021). It has been determined by Bento et al. (2021) that jurisdictions in which other CPIs are implemented lead to the adoption of higher internal prices. This highlights the importance of using multiple CPIs simultaneously to conduct climate mitigation more effectively (Carbon Pricing Dashboard, 2021; Nar, 2020).

2.2.4 Carbon offsetting

The last carbon pricing instrument that will be discussed is carbon offsetting. Carbon offsetting mechanisms are market-based systems where carbon credits are issued from the implementation of carbon reduction projects and sold either domestically or internationally (Carbon Pricing Dashboard, 2021). Through the purchase of carbon credits, actors compensate their own emissions by supporting low-carbon projects elsewhere. It can be thought of as “redistributing responsibility for emissions reductions across sectors or borders” (World Bank, 2021). Some examples of emission reduction projects include reforestation projects, wind farms and implementing efficient cooking stoves in developing countries. (Hyams & Fawcett, 2013). Carbon offsetting can either be voluntary or compliant and, as discussed in Section 2.2.1, it can be used within other CPIs, such as ETSs (Hyams & Fawcett, 2013; Parker, 2019). One of the first offset mechanisms to be implemented was the *Clean Development Mechanism*, introduced by the UN under the Kyoto Protocol (European Commission, Carbon Border Adjustment Mechanism, 2021). The aim of this project was to “stimulate sustainable development and emissions reductions, while giving industrialized countries some flexibility in how they meet their emission reduction” (Hyams & Fawcett, 2013). On top of this, carbon offset mechanisms were expected to create cost-efficient carbon emission reductions and transfer funds and technology from developed to developing countries (Hyams & Fawcett, 2013). In some industries, carbon offsetting remains a central tool to reach the climate objectives under the Paris Agreement. This is particularly true for the aviation sector (Watt, 2021). Indeed, to reach their climate goals, the Civil Aviation Organization introduced the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), complementary to the EU ETS which also touches on a part of the GHG emissions of aviation in the EU (Abeyratne, 2019: Watt, 2021). However, the World Bank has a mitigated opinion on the role that offsetting mechanisms should play. Indeed, “while offsetting can contribute by mobilizing finance and lowering overall mitigation costs, there is increasing debate about how great its role should be" (World Bank, 2021). According to the World Bank (2021), offsetting mechanisms redistribute the responsibility of emitting but have a limited role in deep decarbonization, making it important to question the role of carbon offsetting in the transition towards carbon neutrality.

As an example of offsetting project, the pilot project named *Reducing Emissions from Deforestation and Forest Degradation (REDD+)* was taken to the international stage at COP 11 in 2005. This carbon offset pilot mechanism aimed to reduce carbon emissions from forest loss in tropical countries (Miles, 2021). Indeed, forests are a critical tool to reach the 1.5°C temperature goal (Seymour & Busch, 2016), which makes them a common offsetting opportunity. Through the REDD+ project, "high-emission countries and companies could pay rainforest-rich nations and communities to conserve forests, thus 'offsetting' carbon emissions in one location through the sequestration of carbon in another" (Miles, 2021). In addition to the high expectations in GHG emissions reductions, this projet would bring new income to the local community thanks to the needs of journalists, researchers and project staff when relocating to the surroundings of the forest (Miles, 2021). Unfortunately, the REDD+ project did not only create positive externalities and highlighted common challenges of such mechanisms. The mismatch of information between the community members and the project leaders in determining and monitoring the carbon sequestration as well as its economic worth puts the project leaders (who have access to the internet and to unbiased information on the carbon market) at a serious advantage. These inequalities and lack of transparency among stakeholders tend to hinder the community engagement (Miles, 2021). According to Miles (2021), relationships, trust and long-term security are crucial elements to ensure community engagement in such offsetting mechanisms. The initial expectation for carbon offsetting mechanisms to offer benefits to both developed and developing countries is a claim that can only be respected through the careful implementation of a project, in which ethical concerns are well thought through.

In addition to the uncertainty of benefits for developing countries, offsetting mechanisms have been highly critized for their lack of scientific legitimacy and for the issue of additionality (Hyams & Fawcett, 2013). On the one hand, "although most offset projects are certified through networks of consultants, verifiers, and standards agencies" (Watt, 2021), associating a quantity of carbon reduction to, for instance, planting a tree, is a risky scientific claim. "The rates of carbon sequestration by trees and how this varies over time and by species, the security of savings, the risk to plantations from disease, fire, and so on—in addition to broader ethical issues around what the trees are replacing, whose land it is, and what happens to local people’s rights” are all elements that makes the scientific legitimacy of such projects doubtful (House of Commons Environmental Audit Committee, 2007). *Additionality,* on the other hand, refers to questionning whether the emissions reduction achieved through a project would have taken place regardless of the intervention of an offsetting mechanism (Hyams & Fawcett, 2013). These two elements build up to the doubts of the World Bank about the true role of carbon offsetting mechanisms in decarbonization (2021).

Carbon offsetting is highly controversial and has divided the environmental movement (Hyams & Fawcett, 2013). According to the World Bank (2021), “there is increasing consensus that offsetting should be supplementary to companies’ own emissions reduction as part of their corporate net-zero strategies”. Hyams & Fawcett (2013) agree that carbon offsetting should only be used after significant efforts of emissions abatement have been furnished. However, this is not the case today. Indeed, carbon offsets are commonly used in avoidable situations where individuals purchase carbon credits to discharge their conscience but continue to take part in high carbon activities (Hyams & Fawcett, 2013). This outlines the risk of companies to claim carbon neutrality but who simply pay to offset their emissions and do not engage in any emissions abatement, a concept more commonly known as *greenwashing* (Hyams & Fawcett, 2013). The original intentions of carbon offsetting mechanisms have many positive aspects and, if used appropriately, carbon offsetting could be a driver for the achievement of the Paris Agreement climate objectives. However, to ensure deep decarbonization, carbon offsetting should be used as a complementary tool to other CPIs (World Bank, 2021).

2.3 Climate change and supply chains

It is commonly known that most companies have a significant environmental impact through their daily operations, their supply chain or even the usage or disposal of their products. What is not as often discussed, however, is the impact that climate change has, and increasingly will have, on business operations. Indeed, there are three types of climate change risks that can have an impact on companies : *risks to core operations*, *risks to the value chain* and *risks that arise from broader changes in the economy and infrastructure* (Sussman & Freed, 2008, as cited in Dasaklis & Pappis, 2013). The value chain, or supply chain, is thus significantly exposed to climate change risks. In many industries, supply chains are responsible for more than three quarters of GHG emissions of the company. Indeed, while every link of the supply chain contributes to adding value to the product, it also contributes to environmental degradation (Dasaklis & Pappis, 2013). Every step of the value chain is thus confronted to threats and opportunities linked to climate change, thereby giving the supply chain as a whole "the power to drive environmental action at scale" (CDP, n.d.). Figure 6 portrays some of the common threats and opportunities that supply chains are exposed to due to climate change, as highlighted by Dasaklis & Pappis (2013). In order to face the challenges induced by climate change, there is a critical need for resiliency across the supply chain (CDP, n.d.). This necessity is also recognized by the European

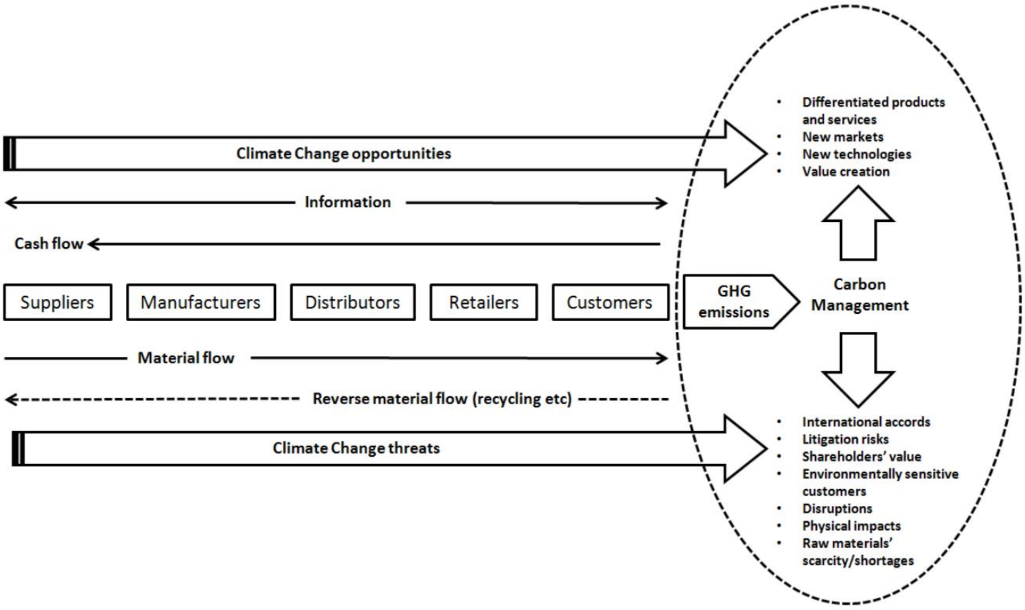


Figure 6 - Climate change threats and opportunitites for supply chains (Dasaklis & Pappis, 2013, p.1141)

Commission. As part of the European Green Deal, the European Commission launched the EU Taxonomy, with the aim of “redirecting money towards sustainable projects and make societies more resilient against climate change” (European Commission, EU Taxonomy for sustainable activities, 2021). To do so, lists of environmental objectives and envrionmentally sustainable economic activities were established to guide companies, investors and policymakers towards sustainable investments. Amongst the six environmental objectives, we have *climate change mitigation, climate change adaptation* and *the transition to a circular economy* (European Commission, Eu taxonomy for sustainable activities, 2021), all of which are objectives that can be tackled through changes in the supply chain. The element of circularity will be discussed further through the use of *closed-loop supply chains* in the next Section.

In this era of transition towards sustainable business, companies who fail to adopt sustainable practices and ignore the threats and opportunities that they face will eventually be at a significant disadvantage (Dasaklis & Pappis, 2013). “Investors, consumers and policymakers want to see companies taking responsibility for the value chain and purchasing decisions” (CDP, n.d.). Indeed, the consumers’ expectations are evolving rapidly and, in addition to high quality products and services at low prices, they are expecting companies to incorporate environmental concerns into their products and services (Dasaklis & Pappis, 2013). Environmentally-sensitive consumers are thus putting an increasing amount of pressure on companies to take part in climate change mitigation. An effective way to respond to this pressure is by implementing green practices throughout the value chain, most commonly known as *Green Supply Chain Management* (GSCM) (Lee et al., 2014).

2.3.1 Green Supply Chain Management

According to Lee et al. (2014), implementing changes in a company’s operations in order to improve its environmental impact will lead to uncertain consequences in the supply chain, which, once again, highlights the need for resiliency as to quickly adapt to these unexpected consequences. GSCM is a vast concept that englobes many possibilities, “ranging from green purchasing, to environmental integration with customers and suppliers, to a closed-loop supply management” (Lee et al., 2014). One of the main strengths of GSCM is its efficient role in *green growth decoupling*. This refers to the possibility of economic growth while simultaneously reducing the environmental impact and is a key element for companies to dare investing in emission reduction strategies (Fahimnia et al., 2013). According to Kumar & Subrahmanya (2022), other advantages of GSCM include significant positive effects on the operational efficiency of a company, in its innovation process and in overall cost reduction, thereby improving the global performance of the organization. Jannat et al. (2019) also mention waste reduction, energy savings and increased business opportunities through an improved brand image as positive side effects of GSCM. However, there is a time lag between the implementation of green practices and the observation of these positive effects, depending on the length and complexity of the supply chain (Kumar & Subrahmanya, 2022).

Indeed, all supply chains are exposed to a phenomenon called the *bullwhip effect* (Lee et al., 2014), which refers to the distortion of information as it is passed along the supply chain. This effect is responsible for the time lag between the implementation of a practice and its consequences as well as for the alterations in scope or precision of the information as it enters and as it exits the value chain. In the case of changes brought to the environmental impact of the supply chain, we are confronted to the *Green bullwhip effect*. Indeed, environmental specifications will be subject to multiple distortions along the value chain (Lee et al., 2014). The risks and uncertainties that revolve around these specifications will force actors along the chain to take additional buffers, longer lead times and amplify the requirements as to be certain to comply with the demand (Lee et al., 2014). This will lead to an overall increased stringency of environmental specifications which doesn’t reflect the original requirements. It is important for managers to be aware of the Green bullwhip effect and to take it into account in discussions with their suppliers (Lee et al., 2014).

A common practice that falls under GSCM is the use of *Closed-loop supply chains* (CLSCs). As opposed to *Open-loop supply chains* which require new input and raw materials, CLSCs aim to recover the products at their end-of-life and reuse or recycle the materials to inject it back into their value chain (Das & Posinasetti, 2015). These practices aim to improve the performance of the supply chain in terms of profit, growth and customer satisfaction by tackling emissions abatement through the reduction of waste and resource depletion (Das & Posinasetti, 2015 ; Fahimnia et al., 2013). CLSCs are thus analogous to the concept of circularity and, as mentioned above, the transition to a circular economy is largely encouraged by the European Commission through the EU Taxonomy (European Commission, Eu taxonomy for sustainable activities, 2021). This means that the implementation of a CLSC is a good step for the company to be recognized as a sustainable economic activity and retain its investors and customers. One aspect of CLSCs that acts as a barrier to its implementation is the increase is environmental footprint for the company in which it is implemented. Indeed, although CLSCs have a positive environmental impact over the whole life-cycle of a product, reusing and remanufacturing it adds steps to the supply chain, thereby increasing its footprint (Das & Posinasetti, 2015). What used to be indirect emissions and therefore not managed by the company become direct emissions and must be included in the company’s footprint (Fahimnia et al., 2013). In conclusion, although overall emissions are reduced, the company is, theoretically, responsible for emitting more. To counteract this unfair and dissuading aspect, subsidies could be given to companies willing to implement a CLSC to compensate the carbon costs associated with this increase in emissions (Fahimnia et al., 2013).

Although there are many drivers to the implementation of GSCM practices, some of which have already been discussed, there are also several barriers that dissuade companies from using such practices. The time lag between the execution of the practice and the observation of rewards is one of them and has already been mentioned. Meager et al. (2020) outline the main barriers in developed countries, some of which are initial costs, inadequate managerial mindset and uncertainty of benefits. In developing countries however, we can find low demand of green products due to lack of awareness and lower incentives from regulations amongst the key barriers of GSCM (Jannat, et al., 2019). The effective implementation of green practices in the supply chain thus depends on the economic environment and may vary between regions or countries. Many companies today have decentralized their supply chain to developing countries in order to benefit from cost reductions in the manufacturing of their goods, but these companies are likely to be confronted to the increasing pressure from customers regarding environmental practices and will need to respond, possibly through the implementation of GSCM practices. Companies will thus impose environmental specifications on their suppliers who will, in turn, need to adopt sustainable practices in order to maintain their partnerships. This portrays the power of market players to spread sustainable business practices (Kumar & Subrahmanya, 2022 ; Schaltegger et al., 2016).

3. Methodology

The first part of this thesis aimed at gaining a solid understanding of the largest emissions abatement mechanisms in place today and to gain insight on their development over the past decades. The next step is to analyze the evolution of their associated carbon prices over time, depending on their location. This will allow for predictions to be made on the further evolution of these carbon prices, which will be used in the optimization models. These models are created with the objective to answer the questions raised : *How should companies react to the uncertainties that revolve around the evolution of the carbon markets?* and *How should they invest strategically as to decarbonize their supply chain today and minimize their costs?*

These questions are addressed through the construction of an optimization model which outlines the supply chain of a fictive company in the manufacturing industry. Based on the insight from the literature review, four different fictive companies are created, each corresponding to a different CPI, carbon prices and/or scope of emissions coverage due to their geolocation. Cost-minimization remains central to all for-profit companies today, regardless of their intentions towards climate change mitigation. Therefore, an optimization model is an appropriate tool to reach the cost-minimization objective while observing strategic decision-making amongst the investment possibilities for CO2e emissions reduction. Furthermore, optimization models can be adapted to several settings such as different CPIs, combinations of them and evolving carbon prices. Indeed, one of the main challenges to this research question is the rapid evolution of carbon prices. The World Bank advocates carbon prices between USD 40–80/tCO2e in order to limit global warming to 1.5°C but, considering that 96.34% of carbon prices today are below this range, Wood Mackenzie claims that prices will need to reach USD 160/tCO2e by 2030 to reach the same climate target (World Bank, 2021; Wood Mackenzie, 2021). This shows the uncertainty of how the carbon prices will evolve, although they will most likely increase over time so as to respond to the climate emergency. In order to take the evolution of carbon prices into consideration in the optimization models, a stochastic programming approach will be used. This will allow for the uncertainty of the future to be included in the strategic decision-making process of the companies today.

To best address the questions raised, the models will be built around a simplistic supply chain. This will allow for the decision variables of the models to focus on investment and strategic decisions rather than operational ones. Another reason for using a basic supply chain is the capacity to adapt it to many different companies and industries.

The most laborious part of data collection concerned the carbon prices across CPIs and across the world. The carbon prices used in the models are based on data collected from three main sources : the *States and trends of carbon pricing* reports from the World Bank (years 2016 to 2021) which outline the carbon prices along with the CPI in place in each country, the *Carbon Pricing Dashboard* website from the World Bank which regroups information on the implementation of all carbon pricing initiatives worldwide, and the *CarbonCredits.com* website which gives more precise pricing evolutions for several CPIs as well as real-time prices on several carbon markets.

Based on the literature review of the CPIs implemented across the world, four settings were chosen for the companies : company A subject to the EU ETS, company B subject to the EU ETS and the Luxemburg carbon tax, company C subject to the California CaT and company D subject to Internal Carbon Pricing. These four scenarios were chosen so as to analyze the results of the optimization for the most likely real-life situations. Indeed, the EU ETS has a carbon price in the upper range while the California CaT has a lower carbon price but a wider coverage of emissions. In many European countries, complementary carbon taxes are implemented on areas that are not covered by the EU ETS, such is the case in Luxemburg. Company D is located in a country with no national or subnational CPI in place but is voluntarily performing ICP with, as reference, the recommended carbon price by Wood Mackenzie in order to adequately prepare for the likely evolution of carbon prices.
Offsetting mechanisms will not be used in any of the models, for several reasons. First of all, as highlighted in Section 2.2.4, the role of carbon offsetting in deep decarbonization is questionable and, since the goal of this exercise is to identify areas for supply chain decarbonization, it is not suitable to use carbon offsetting in this context. Furthermore, the price of offsetting highly depends on the project and its location, making it difficult to use in the models.

Emissions abatement investments such as the ones proposed in the models below (see Table 4) involve significant costs for their implementation but also lead to reductions in future operational and carbon costs. CPIs are continuously becoming a more important share of every company’s costs, meaning that the evolution of carbon prices needs to be taken into account to ensure profitability in the long run. In order to decide strategically which investments to make, all models are first solved for the year 2030. This time frame was chosen as it corresponds to crucial moments in both ETSs. For the EU ETS, 2030 is the year in which the 4th phase of the system will end, leading to probable changes in the regulations and cap decrease rate, thereby influencing the carbon market. For the California CaT, 2030 is the year for which the current regulations have been set through the California Global Warming Solutions Act, meaning that changes are likely to occur after this date which will, once again, influence the carbon market. Then, the models are optimized for the year 2035 in order to observe whether changes occur when a longer time frame is considered.

To include the evolution of the carbon market in the models, the carbon prices used for the EU ETS and the California CaT have been forecasted based on the historical data collected. In order to take into account the uncertainty of this evolution, the models for Companies A, B and C are stochastic optimization models consisting of two stages. The first stage consists of minimizing the costs that are known today (mainly the operational costs and the investments costs). Then, the second stage consists of minimizing the expected carbon costs with carbon prices that are not yet known, for which expected (or forecasted) values are required, along with their probabilities of occurrence. To these ends, the *forecast.ets* function in Microsoft Excel was used on the historical data collected, resulting in a mean forecasted value and a 95% confidence interval bounded by lower and upper price values for each ETS. These forecasts, which are assumed to be normally distributed, are then used to determine the carbon prices to be used to in the models along with their probabilities of occurrence. In order to dive deeper into the future and the evolution of the carbon market, two other scenarios are drawn, one with a low level of uncertainty regarding the evolution of carbon prices after 2030, and one with a high level of uncertainty. These two scenarios are based on the outcomes of the 2030 forecast and are used to forecast carbon prices for the year 2035.

In order to take the analysis a step further, different levels of risk aversion are included in the different models. Indeed, given the uncertainty linked to the evolution of the carbon prices and their growing significance in a company’s costs, it would make sense for a company to show aversion to the risk of highly increasing carbon prices. To portray this in the optimization models, disutility factors are used for each scenario in the objective function. Given that the models are subject to a cost minimization and not a profit maximization, exponential *disutility* functions are used rather than the traditional *utility* functions. To represent different levels of risk aversion (low, medium and high), three different exponential functions are used to determine the disutility factors associated with each pricing scenario (see Section 4.2.2 for more details). These disutility factors will allow the risk aversion of the companies to be included in the models by adding more weight to the scenarios of higher costs (both carbon costs and operational costs) than the ones of lower costs.

The parameter values used in the optimization model are estimations based on data from the ADEME database and general assumptions. These assumptions and their associated values are outlined Table 25 and Table 26 of the Appendix. The values used are in accordance with the general simple-mindedness of the model with the sole purpose to illustrate the proportion of emissions linked to each part of a supply chain. The implementation costs of each investment are assumed to be absorbed by the company over a 5 years period. A loan equal to the overall investment costs is thus taken in order to allow for the investment to be made and has to be paid back over 5 years with an interest rate of 10%. The investment costs present in the model are thus equivalent to a fifth of the overall investment cost, plus the interest rate. This is done in order to reflect a real-life procedure when a company is faced with investment opportunities. Indeed, companies very often rely on loans to be able to transform their supply chain, and these costs need to be included in the decision-making process.

Once the models have been optimized and the results collected, the main variables to observe and discuss are the investments that are done and the type of packaging that is chosen. Tables are thus drawn to outline the results of these two variables depending on the pricing scenarios and the risk aversion level. These tables can be found in Sections 4.4.1 to 4.4.4. Despite the lack of ground for comparability between the different companies, a discussion is held around their reaction to several pricing scenarios and risk aversion levels. This discussion can be found in Section 5 and revolves mainly around the differences in investment decisions of the various companies. As already mentioned above, it is important to emphasize that, due to the subjectivity of the models, the discussion will not include any conclusions on the right or better investments to make for a company and, therefore, no analysis will be done on those results alone.

4. Model

4.1 Explanation of the model

The optimization models below are based on the supply chain of a fictive company with simplistic features. The objective of this optimization is not to work with a complex supply chain in a specific industry but rather to focus on the opportunities for carbon emissions reductions in order to highlight the strategic decision making of companies under different regulatory systems and for different evolutions of the carbon market over time. Another advantage of building a simplistic model is its capacity to be adapted to different companies across industries.

The supply chain portrayed in the model uses a single type of input in the two-steps manufacturing process to produce a single product as output. The product then undergoes individual packaging before being transported by truck to the National Distribution Centre (NDC) for storage. Then, the products are sent out to the different Selling Points (SPs) where they are sold to the customers. Currently, the manufacturing and the storage facilities are powered by grey electricity from the grid. The products are transported from the manufacturing facility to the NDC and then to the SPs by thermic diesel trucks.

In order to decarbonize the supply chain, several investments can be made, each representing different levels of emissions abatement and costs, and are summarized in Table 4. The five possibilities have been chosen because they can be easily-implemented but the list is non-exhaustive. It is important to note that these investments represent internal changes to the company and do not alter the general outline of the supply chain (other than a reverse loop being created for investment n°5). As previously mentioned, the list of possible alterations is endless but only decisions that are internal to the company have been chosen for the sake of this exercise.

Table 4 - Potential investments and decisions for emissions abatement

	Investments :
1)	Investment in solar panels to cover the energy needs of the supply chain facility and thereby reduce emissions by no longer purchasing grey electricity.
2)	Investment in new machinery that will increase the energy efficiency of the second step of the manufacturing process.
3)	Construction of 3 RDCs that will cut down the total distance covered by trucks for the distribution of the products. Solar panels are used to cover the energy needs of the facilities. The construction however induces carbon emissions that need to be taken into account.
4)	Investment in electric vans to cover transportation between RDCs and SPs. The vans can be charged using the solar panels at the RDCs.
5)	Implementation of a CLSC. Old products are recovered at SPs and brought back to the RDCs (if built), then to the NDC and finally to the factory where they undergo the "recycling" stage. 50% of the material is thereby recovered and can be reused in the manufacturing process, the rest is disposed of.

Moreover, three packaging possibilities have been chosen, each associated to a certain cost and emissions level per unit of product. These options are represented in Table 5.

Table 5 - Possibilities of packaging material

	Packaging :
1)	Polyethylene terephthalate (0.0541 kgCO2e/unit)
2)	Cardboard (0.0057 kgCO2e/unit)
3)	Polystyrene (0.0482 kgCO2e/unit)

Figure 7 below outlines the structure of the supply chain. The green stars indicate the investment opportunities and decisions for emissions abatement. As previously mentioned, the structure of the supply chain stays the same regardless of the investments chosen by the companies, since there are no new external factors influencing the forward flow of the products. The only alteration to the structure comes from the implementation of a CLSC.

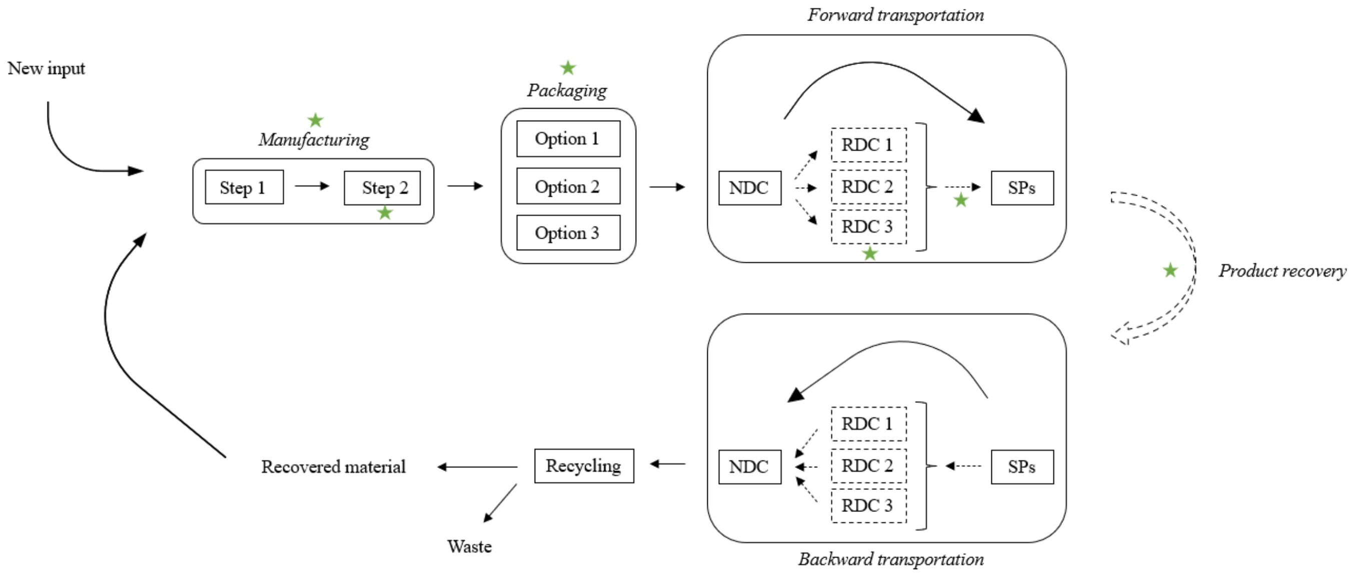


Figure 7 - Outline of the supply chain

The five abatement opportunities suggested here each have different implications on the company. They all have an associated investment cost for their implementation but usually result in operational cost reductions in the long-term through, for instance, energetical independence, waste reduction, material recovery and divergence from fossil fuels. On top of the operational cost reductions from the investments, significant savings will be generated due to a lower carbon budget and thus less severe implications of the carbon regulations (ETS, carbon tax, etc.). When it comes to investing in product recovery (investment n°5), it has special implications for the company and its total emissions budget. Indeed, as discussed in Section 2.3.1, the implementation of a CLSC often increases the total carbon emissions budget of a company even though it has a positive effect on the environment. This is due to the lack of consideration of emissions linked to the waste generated at the disposal of the product. The repercussions of this phenomenon will be discussed in Section 5.

Several assumptions were made as to further simplify the operations aspect of the model. These assumptions are summarized in Table 6 below.

Table 6 - Model assumptions

1.	The demand is constant and fully satisfied every day and there is sufficient capacity to cover the daily demand.
2.	If investment n°5 is done, the recycling process will be located in the same facility as the manufacturing facility. There is thus no need to build additional buildings and the recycling system will be linked to the energy system in place in the manufacturing facility. The recycling process will require 500kWh of electricity daily.
3.	The daily electricity consumption of the manufacturing process before and after investment n°2 is 2500kWh and 1625kWh respectively.
4.	The emissions linked to each packaging type include both the production and the disposal of them.
5.	The costs induced by each investment are absorbed by the company overs a five years period. Loans are taken out at the time of the investment and need to be paid back in five year with a 10% interest rate.
6.	The distance covered by trucks includes transport to the NDCs as well as to the RDCs (if built) and to the SPs.
7.	There is no material quality loss in the recovered input from the recycling process. The amount of recovered product is assumed to be constant and equal to 50 units daily.

4.2 Carbon prices forecasting - Stochastics

As mentioned in Section 3, an important part of the modeling is to determine the future carbon prices for each model along with their uncertainty of occurrence. To these ends, the historical carbon prices for the EU ETS and the California CaT were collected, from the 1st of October 2018 and the 1st of July 2017, respectively, and can be found in Table 14 and Table 15 of the Appendix. These historical data are used to predict the future carbon prices of both ETSs. For the EU ETS, the forecast is run for the year 2030, the year in which the 4th phase of the system will end and after which there will be probable changes in the regulations and cap decrease rate, thereby influencing the carbon market. For the California

CaT, the forecast is also run for the year 2030, the year for which the current regulations have been set through the California Global Warming Solutions Act (California Legislative Information, 2006), meaning that changes are likely to occur after this date which will, once again, influence the carbon market.

As mentioned in Section 3, the Microsoft Excel function *forecast.ets* was used to predict the evolution of the carbon markets. This function uses an Exponential Smoothing ETS algorithm, thereby using a weighted sum in which the weight of past observations is decreased exponentially to generate the prediction. The seasonality was set to zero, considering that carbon prices do not fluctuate periodically and a confidence interval of 95% was used. The function returns a mean forecasted value, as well as a lower and an upper bound given the confidence interval, as shown graphically on Figure 8. The data is considered to be normally distributed with as mean the forecasted value and a 95% probability of lying within the bounds. As per the normal distribution and using graphical representations, probabilities are assigned to the mean and to lower and upper price values, both one standard deviation away from the mean, giving rise to three pricing scenarios. The obtained results are shown in Table 7 below.

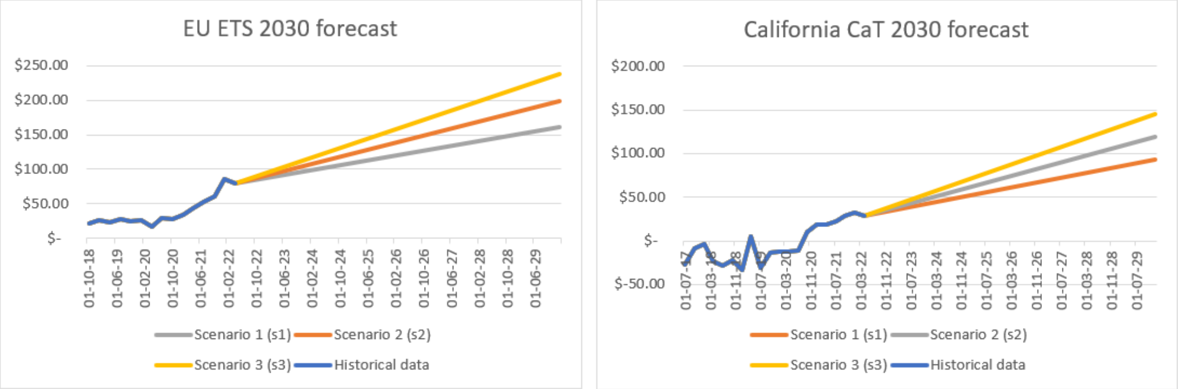


Figure 8 - Graphical forecast for the year 2030

Table 7 - Forecasted prices for the year 2030

	EU ETS	**California CaT**
Lower price – Scenario 1 (s1)	USD 170.17/tCO2e *Probability (p1) = 13.6%*	USD 99.65/tCO2e *Probability (p1) = 13.6%*

Mean price – Scenario 2 (s2)	USD 198.99/tCO2e *Probability (p2) = 68.3%*	USD 119.25/tCO2e *Probability (p2) = 68.3%*
Upper price – Scenario 3 (s3)	USD 227.82/tCO2e *Probability (p3) = 13.6%*	USD 138.86/tCO2e *Probability (p3) = 13.6%*

4.2.1 Long-term forecast under low and high uncertainty

It is interesting to look past the year 2030 and hypothesize on how the carbon market might evolve from there. Two cases are thus drawn, one with a low level of uncertainty linked to the evolution of the carbon market after 2030 and one with a higher level of uncertainty. To represent these two cases and determine the associated carbon prices, the slopes of the evolution of the carbon prices between 2022 and 2030 are calculated. Then, they are used to simulate low and high uncertainty with a small spread between the slopes or a high spread between the slopes, respectively. Under low uncertainty, the spread between the slopes of the upper, mean and lower prices is the same as the spread between the slopes of the three forecasted prices for 2030. This difference is however doubled to simulate a high uncertainty for the other case. These two cases for the EU ETS are represented graphically by Figure 9. The details of the calculations can be found in the Appendix along with the graphical representations for California CaT. For the year 2035, we now have nine different forecasts (the nine outcomes that can be seen on the trees of Figure 9). Once again, these forecasts are assumed to be normally distributed, thereby allowing five carbon prices to be highlighted on the normal distribution curve along with their probabilities of occurrence. This gives rise to new scenarios : scenarios 4-8 represent the five different carbon prices under low uncertainty of the evolution of the carbon market and scenarios 9-13 represent the five different carbon prices under high uncertainty. These scenarios and their associated probabilities as per the normal distribution are outlined in Table 8.

It is important to note that the models rans for the year 2035 remain two-stages models. Indeed, the carbon prices forecasted for the year 2030 are simply used as a basis to forecast the carbon prices for the year 2035 and are not used as a stage in the model.

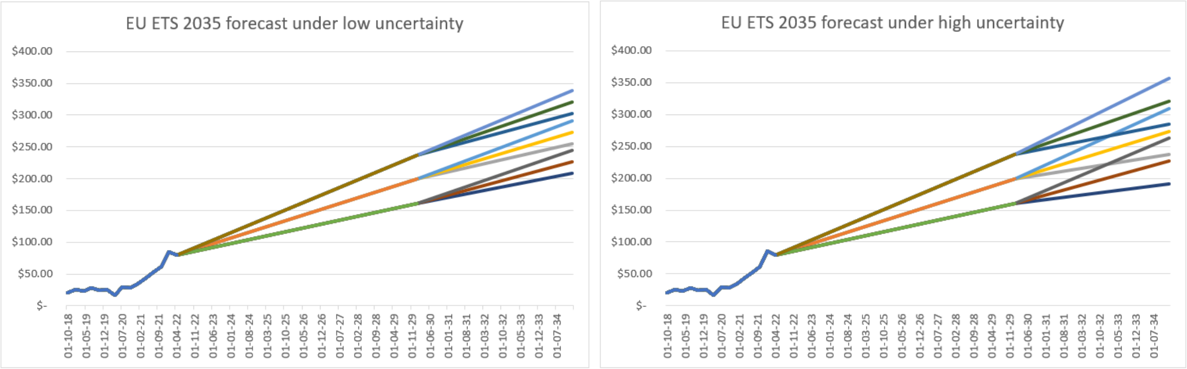


Figure 9 - EU ETS 2035 forecast - low and high uncertainty

Table 8 - Carbon prices for the year 2035

	EU ETS **Low uncertainty**	**EU ETS** **High uncertainty**	**California CaT** **Low uncertainty**	**California CaT** **High uncertainty**
Lower price *Probability (p4)* *= 2.13%*	*Scenario 4 (s4)* USD 219.39/tCO2e	*Scenario 9 (s9)* USD 204.38/tCO2e	*Scenario 4 (s4)* USD 139.17/tCO2e	*Scenario 9 (s9)* USD 128.96/tCO2e
Mid-low price *Probability (p5)* *= 13.6%*	*Scenario 5 (s5)* USD 241.01/tCO2e	*Scenario 10 (s10)* USD 232/tCO2e	*Scenario 5 (s5)* USD 153.87/tCO2e	*Scenario 10 (s10)* USD 147.75/tCO2e
Mean price *Probability (p6)* *= 68.3%*	*Scenario 6 (s6)* USD 273.43/tCO2e	*Scenario 11 (s11* USD 273.43/tCO2e	*Scenario 6 (s6)* USD 175.92/tCO2e	*Scenario 11 (s11)* USD 175.92/tCO2e
Mid-high price *Probability (p7)* *= 13.6%*	*Scenario 7 (s7)* USD 305.86/tCO2e	*Scenario 12 (s12)* USD 314.48/tCO2e	*Scenario 7 (s7)* USD 197.97/tCO2e	*Scenario 12 (s12)* USD 204.22/tCO2e
Upper price *Probability (p8)* *= 2.13%*	*Scenario 8 (s8)* USD 327.48/tCO2e	*Scenario 13 (s13)* USD 342.48/tCO2e	*Scenario 8 (s8)* USD 212.65/tCO2e	*Scenario 13 (s13)* USD 223/tCO2e

This leads us to three different cases to be applied to the model for each company :

Case 1 : Model optimized for the year 2030 with three price levels and their associated probabilities (Scenarios 1 – 3).
Case 2 : Model optimized for the year 2035, based on the forecasted prices in 2030, with a *low level of uncertainty* regarding the evolution of the carbon market. Five carbon prices are used along with their probability of occurrence (Scenarios 4 – 8).
Case 3 : Model optimized for the year 2035, based on the forecasted prices in 2030, with a *high level of uncertainty* regarding the evolution of the carbon market. Five carbon prices are used along with their probability of occurrence (Scenario 9 – 13).

4.2.2 Reaction to risk

The uncertainty of the carbon market evolution exposes the companies to the risk of seeing their costs increase significantly. The higher the carbon prices, the more the companies and their supply chains will be impacted. It is thus logical for companies to present aversion to the risk of high carbon prices. In order to prepare for such an event, scenarios of high prices need to be considered with more caution than scenarios of lower prices. To do so, a utility function, or in this case, because it is a cost minimization, the *disutility* function, representing the risk aversion of a company will be used in the models. The parameter u_s, which represents the disutility factor that the company associates to scenario *s*, will be included in the objective function and will add increasingly more weight to the higher costs scenarios compared to the lower costs scenarios. The disutility factor of each scenario is calculated by using multiple exponential disutility functions, in which the ratios between the carbon prices of the scenarios are injected. The different functions represent low, medium and high risk aversion and can be found in Table 9 (for the EU ETS) and Table 10 (for the California CaT) along with the resulting disutility factors. The details of the calculations can be found in Table 19 to Table 24 of the Appendix.

Table 9 - EU ETS - Disutility ratios

Scenario	**Carbon Price (USD)**	**Disutility (low risk aversion)** $f(x) = 2^x$	**Disutility (medium risk aversion)** $f(x) = 3^x$	**Disutility (high risk aversion)** $f(x) = 4^x$
s1	170.17	1	1	1
s2	198.99	1.125	1.205	1.266
s3	227.82	1.266	1.453	1.602
s4	219.39	1	1	1
s5	241.14	1.071	1.115	1.147
s6	273.43	1.186	1.311	1.407
s7	305.86	1.314	1.542	1.727
s8	327.48	1.407	1.718	1.980
s9	204.38	1	1	1
s10	232	1.098	1.160	1.206
s11	273.43	1.264	1.449	1.597
s12	314.48	1.453	1.807	2.110
s13	342.48	1.597	2.101	2.552

Table 10 - California CaT - Disutility ratios

Scenario	**Carbon Price (USD)**	**Disutility (low risk aversion)** $f(x) = 2^x$	**Disutility (medium risk aversion)** $f(x) = 3^x$	**Disutility (high risk aversion)** $f(x) = 4^x$
s1	99.65	1	1	1
s2	119.25	1.146	1.241	1.313
s3	138.86	1.314	1.541	1.725

s4	139.17	1	1	1
s5	153.80	1.076	1.122	1.157
s6	175.92	1.201	1.337	1.442
s7	197.97	1.340	1.591	1.796
s8	212.65	1.442	1.786	2.079
s9	128.96	1	1	1
s10	147.75	1.106	1.174	1.224
s11	175.92	1.287	1.492	1.657
s12	204.22	1.499	1.899	2.249
s13	223	1.658	2.228	2.748

Every case described on page 41 will be optimized for each of the three levels of risk aversion (low, medium and high) and their influence on the results will be discussed in Section 5.

4.3 Construction of the model

The sets, parameters, variables and constraints outlined below are common to the models of all four companies and will therefore only be laid out once to avoid repetition. Table 26 in the Appendix portrays the numerical values used for the parameters. As mentioned in Section 3, these values are educated guesses and are associated to a small-sized factory which requires 2500kWh of electricity daily to cover the production of 10 000 units of products. More information on the provenance of each value can be found in Table 25 of the Appendix. All four companies are operational six day per week, or 310 days a year. In practice, since the compliance period varies between the different CPIs, the carbon prices may change from one period to the next, thereby slightly altering the total costs. However, this slight divergence is likely not to have an impact on the results of the model and, for simplification and comparison purposes, a period of one year will be considered for all models. To these ends, the optimization models will be run for a one year period, at the end of which the company has to have acquired carbon credits equivalent to its emissions covered by the CPI(s) in place.

Sets :

Three indices are created, each corresponding to a different set. The index *i* can take the value 1 to 5 and represents the possible investments to be made. The index *p* corresponds to the types of packaging and can take the value 1 to 3. Lastly, the index *s* represents the different pricing scenarios outlined in Section 4.2.1, ranging from 1 to 13.

i ≙ investments (i = 1..5)

p ≙ packaging (p = 1..3)

s ≙ scenarios (s = 1..13)

Parameters :

The different parameters used in the models are all laid out below along with their description and unit. The value used for each of them can be found in Table 26.

D ≙ Daily demand and production (units)

CI ≙ Cost of one unit of new input (USD)

EI ≙ Emissions linked to the use of one unit of new input (kgCO2e)

EMI ≙ Daily emissions of manufacturing process from energy consumption before investment n°2 (kgCO2e)

EMF ≙ Reduction in daily emissions of manufacturing process from energy consumption after investment n°2 (kgCO2e)

EMP ≙ Emissions linked to the manufacturing of one product (kgCO2e)

CMI ≙ Daily cost of manufacturing process from energy consumption before investment n°2 (USD)

CMF ≙ Reduction in daily cost of manufacturing process from energy consumption after investment n°2 (USD)

$CPack_p$ ≙ Unit cost of packaging p (USD)

$EPack_p$ ≜ Emissions per unit of packaging p (kgCO2e)

$CInv_i$ ≜ Cost of investment i (USD)

$EInv_i$ ≜ Emissions from implementing investment i (kgCO2e)

DI ≜ Distance covered by truck(s) without RDCs (km)

DF ≜ Reduction of distance covered by truck(s) with RDCs (km)

CF ≜ Cost of fuel per km (USD)

EF ≜ Emissions of fuel per km (kgCO2e)

CR ≜ Daily cost of recycling process from energy consumption (USD)

ER ≜ Daily emissions of recycling process from energy consumption (kgCO2e)

ERP ≜ Emissions linked to the recycling process of one product (kgCO2e)

EWR ≜ Emissions from waste generated due to the recycling of one product (kgCO2e)

QRP ≜ Quantity of products recovered daily (units)

QRI ≜ Quantity of input recovered daily (units)

EEOL ≜ Emissions from waste disposal of one product at its end of life (kgCO2e)

p_s ≜ Probability of occurrence of scenario *s*

c_s ≜ Carbon price associated to scenario *s*

u_s ≜ Disutility factor associated to scenario *s*

Variables :

NewRM represents the units of new input that are used daily and depends on the quantity of recovered input from the reverse loop of the supply chain, and thus depends on the implementation of investment n°5.

$$\boldsymbol{NewRM_i} = D - (QRI \times Inv_{i=5})$$

Inv_i is a binary variable and takes the value 1 whenever an investment *i* is chosen.

$\boldsymbol{Inv_i}$ **= 1** if investment *i* is chosen, 0 otherwise

$Pack_p$ is also a binary variable, forced to take the value 1 for the packaging type chosen.

$\boldsymbol{Pack_p}$ **= 1** if packaging *p* is used, 0 otherwise

<u>Variables associated to the operational costs :</u>

The costs of raw materials depend on the quantity of new input multiplied by the cost of one unit of input (CI).

Material costs: $MatCosts_i = (NewRM_i \times CI) \qquad \forall\, i = 5$

The costs of packaging depend on the type of packaging chosen. The cost of one unit of this packaging is then multiplied by the daily demand, since the products are packaged individually.

Packaging costs : $PackCosts_p = \sum_{p=1}^{3} (D \times CPack_p \times Pack_p)$

DI is the initial distance covered, before any investments are done. The original transport cost thus corresponds to this distance multiplied by the cost of fuel per km (CF). Then, if investment n°3 is chosen, it reduces this distance by DF and the transport cost by DF multiplied by CF. Lastly, if investment n°4 is done, it further reduces the distance covered to reach zero if investment n°4 is done, since the usage of electric vehicles does not require any fuel (electricity generated from the solar panels to charge the vehicles).

Transport costs :

$TransCosts_i = (DI \times CF) - (DF \times CF \times Inv_{i=3}) - (DI - DF) \times CF \times Inv_{i=4}$

CMI is the initial cost of the manufacturing process from its energy consumption. If investment n°1 is done, the cost is brought down to zero. If investment n°2 is done, it is decreased to CMF. As a reminder, investments n°1 and n°2 cannot both be chosen.

Manufacturing costs : $ManuCosts_i = (CMI - CMI \times Inv_{i=1} - CMF \times Inv_{i=2})$

The costs induced by the investments is simply the sum of all the implementation costs of the chosen investments.

Investment costs: $InvCosts_i \ = \sum_{i=1}^{5} CInv_i \times Inv_i$

The yearly operational costs is equal to each of the operational costs outlines above multiplied by the number of days that the factory is active in a year (310 days), plus the investment costs.

$$YearlyOpCosts_{i,p} = \left[\left(MatCosts_i \ + \ PackCosts_p \ + \ TransCosts_i \ + \ ManuCosts_i\right) \times \ 310 \ + \ InvCosts_i\right] \quad \forall\, i\,, \forall\, p$$

<u>**Constraints :**</u>

The models are subject to multiple constraints. The first one enforces that only one type of packaging is chosen. The second and third constraints concern the investments. The first of the two states that investment n°4 (purchasing electric vans) cannot be done if investment n°3 (building RDCs) is not done, since the electric vehicles are only useful to cover the shorter distances from the RDCs to the selling point, and not from the NDC to the SPs. The third constraint in the list below imposes that investment n°1 and n°2 cannot both be chosen. This is not so much a hard constraint as a logical one as, if investment n°1 (implementation of solar panels) is done, the energy independence of the company will make investment n°2 (investment in energy-efficient machinery) worthless financially. The last three constraints below are the binary and non-negativity constraints, forcing the variable NewRM to be a positive integer and the variables Inv_i and $Pack_p$ to be binary.

$$\sum_{p=1}^{3} Pack_p \ = \ 1$$

$$Inv_{i=4} \ \leq \ Inv_{i=3}$$

$$Inv_{i=1} \ + \ Inv_{i=2} \ = \ 1$$

$NewRM_i \geq 0 \qquad \forall\, i = 5$

$NewRM_i \in \mathbb{Z} \qquad \forall\, i = 5$

$Inv_i, Pack_p \in \{0{,}1\} \qquad \forall\, i, \forall\, p$

4.3.1 Company A - EU ETS

For the sake of this exercise, company A will be assumed not to be confronted by carbon leakage and is thereby not eligible for free distribution of carbon credits, thereby forced to bid on the carbon market through auctions. In the context of company A, the emissions covered by the EU ETS include CO2e emissions from electricity generation and from the manufacturing process. Emissions from all other parts of the supply chain will thus be ignored. The carbon prices, probabilities of occurrence and disutility factors used for this model can be found in Table 9 and Table 10 of Section 4.2 above.

Additional variables :

Carbon costs :

The same logic as for the manufacturing costs is used to determine the carbon costs associated to the manufacturing process. The only difference is the addition of the emissions linked to the manufacturing of one unit of product during the process (EMP) multiplied by the daily demand.

Manufacturing : $ManuCC_i = (EMI - EMI \times Inv_{i=1} - EMF \times Inv_{i=2} + EMP \times D)$

There are emissions linked to the energy requirements of the recycling process (ER) as well as to the recycling of each product (ERP). If investment n°5 is done, ERP is multiplied by the quantity of recovered products (QRP) and added to ER. Then, if investment n°1 is done, the emissions from the energy usage disappear.

Recycling process : $RecycleCC_i = (Inv_{i=5} \times (ERP \times QRP + ER) - ER \times Inv_{i=1})$

Since the emissions of both processes are calculated per day, they are multiplied by 310 to account for the yearly emissions.

$$YearlyEmissions_i = [(ManuCC_i + RecycleCC_i) \times 310] \qquad \forall\, i = 1,2,5$$

Objective function :

Given the emissions coverage of the EU ETS, the objective function only includes the carbon costs of the processes outlined above and is as follows :

$$minimize \sum_{s=1}^{S} \left[(p_s \times u_s) \times \left(\left(c_s \times \sum_{i=1}^{5} YearlyEmissions_i \right) + \sum_{i=1}^{5} \sum_{p=1}^{3} YearlyOpCosts_{i,p} \right) \right]$$

4.3.2 Company B – EU ETS & Luxemburg Carbon Tax

Company B is subject to both the EU ETS and the Luxemburg Carbon Tax. This means that the coverage of emissions is broader than for company A. Indeed, the Luxemburg carbon tax covers emissions from diesel in transport as well as energy from construction. This means that the transport of the products by truck as well as investment n°3 are now impacted by the tax. The carbon tax in Luxemburg has been introduced in 2021 and its value will thus be taken as it is since no prediction can be done based on its evolution. The carbon prices, probabilities of occurrence and disutility ratios used for the emissions covered by the EU ETS are identical to the ones used in the model for Company A and can be found in Table 8 and Table 9. The carbon prices used for the emissions covered by the Luxemburg carbon tax is 40.12 USD/tCO2e for diesel (trucks) and 23.49 USD/tCO2e for all other energy products.

Additional variables :

As a reminder, the yearly operational costs are as follows :

$$YearlyOpCosts_{i,p} = \left[\left(MatCosts_i + PackCosts_p + TransCosts_i + ManuCosts_i\right) \times 310 + InvCosts_i\right] \quad \forall\, i, \forall\, p$$

Carbon costs :

Manufacturing : $ManuCC_i = (EMI - EMI \times Inv_{i=1} - EMF \times Inv_{i=2} + EMP \times D)$

Recycling process : $RecycleCC_i = (Inv_{i=5} \times (ERP \times QRP + ER) - ER \times Inv_{i=1})$

The carbon costs of transport are calculated identically to the operational costs of transport, with the emissions of fuel (EF) replacing the costs of fuel.

Transport :
$TransCC_i = (DI \times EF) - (DF \times EF \times Inv_{i=3}) - (DI - DF) \times EF \times Inv_{i=4}$

Only investment n°3 is included in the emissions coverage of this CPI. Therefore, only the emissions linked to the implementation of that investment are considered, if it is chosen.

Investments : $InvCC_i = Inv_{i=3} \times EInv_{i=3}$

The yearly emissions covered by the EU ETS are identical to that of company A and are as follows :

$$YearlyEmissionsEUETS_i = [(ManuCC_i + RecycleCC_i) \times 310] \quad \forall\, i = 1,2,5$$

The emissions covered by the Luxemburg carbon tax in addition to the EU ETS are :

$$YearlyEmissionsLuxTax_i = [(TransCC_i) \times 310 + InvCC_i] \quad \forall\, i = 3,4$$

Objective function :

Given the emissions coverage of the EU ETS complemented by the Luxemburg carbont ax, the objective function includes the carbon costs of the processes outlined above and is as follows :

$$minimize \sum_{s=1}^{S} \Bigg[(p_s \times u_s) \times \left(\left(c_s \times \sum_{i=1}^{5} YearlyEmissionsEUETS_i \right) + \sum_{i=1}^{5} \sum_{p=1}^{3} YearlyOpCosts_{i,p} \right) \Bigg] + \sum_{i=1}^{5} [(TransCC_i \times 310 \times CarbonTaxDiesel) + (InvCC_i \times CarbonTaxOther)]$$

4.3.3 Company C – California CaT

Company C is subject to the California CaT. This CPI has a much wider coverage than the EU ETS and, in this case, has a scope equivalent to company B. Indeed, this regulation covers emissions from the industry, transport, power and buildings sectors. The carbon prices used in this model along with their probabilities of occurrence and the disutility factors used to represent to different risk aversion levels can be found in Table 8 and Table 9.

Additional variables :

As a reminder, the yearly operational costs are as follows :

$$YearlyOpCosts_{i,p} = \left[\left(MatCosts_i + PackCosts_p + TransCosts_i + ManuCosts_i \right) \times 310 + InvCosts_i \right] \qquad \forall\, i\,, \forall\, p$$

Carbon costs :

Manufacturing : $ManuCC_i = (EMI - EMI \times Inv_{i=1} - EMF \times Inv_{i=2})$

Transport : $TransCC_i = (DI \times EF - DF \times EF \times Inv_{i=3} - (DI - DF) \times EF \times Inv_{i=4})$

Investments : $InvCC_i = Inv_{i=3} \times EInv_{i=3}$

Recycling process : $RecycleCC_i = (ER \times Inv_{i=5} - ER \times Inv_{i=1})$

$$YearlyEmissions_i = [(ManuCC_i + RecycleCC_i + TransCC_i) \times 310 + InvCC_i] \quad \forall\, i$$

Objective function :

Given the emissions coverage of the California CaT, the objective function only includes the carbon costs of the processes outlined above and is as follows :

$$minimize \sum_{s=1}^{S} \left[(p_s \times u_s) \times \left(\left(c_s \times \sum_{i=1}^{5} YearlyEmissions_i \right) + \sum_{i=1}^{5} \sum_{p=1}^{3} YearlyOpCosts_{i,p} \right) \right]$$

4.3.4 Company D – Internal Carbon Pricing

Company D is not subject to a national nor subnational CPI. However, a voluntary CPI has been implemented. Company D is performing internal carbon pricing throughout its entire supply chain. Scope 1, 2 and 3 emissions are included in this model. The carbon price used is the one recommended by Wood Mackenzie in order to reach the the objectives of the Paris Agreement : 160 USD/tCO2e.

Additional variables :

As a reminder, the yearly operational costs are as follows :

$$YearlyOpCosts_{i,p} = \left[(MatCosts_i + PackCosts_p + TransCosts_i + ManuCosts_i) \times 310 + InvCosts_i\right] \quad \forall\, i, \forall\, p$$

Carbon costs :

Manufacturing : $ManuCC_i = (EMI - EMI \times Inv_{i=1} - EMF \times Inv_{i=2})$

Transport : $TransCC_i = (DI \times EF - DF \times EF \times Inv_{i=3} - (DI - DF) \times EF \times Inv_{i=4})$

The emissions induced by the implementation of all five investments are to be considered, if chosen.

Investments : $InvCC_{\boldsymbol{i}} = Inv_{i=3} \times EInv_{i=3}$

Recycling process : $RecycleCC_i = (ER \times Inv_{i=5} - ER \times Inv_{i=1})$

The emissions linked to the use of new raw materials (EI) are to be taken into account. These costs depend on whether input is recovered through the recycling process and is therefore linked to the quantity of new raw materials.

Input : $InputCC_i = EI \times NewRM_i \quad \forall\, i = 5$

Each type of packaging is responsible for a certain amount of emissions per unit ($EPack_p$),

which, multiplied by the daily demand, reflects the daily quantity of emissions for the packaging chosen thanks to the binary variable $Pack_p$.

Packaging : $PackCC_p = \sum_{p=1}^{3} EPack_p \times D \times Pack_p$

On top of the emissions linked to the running of the recycling process, the model includes the emissions that arise from the waste created during the recycling of one product (EWP). This quantity is multiplied by the number of products recovered daily, if investment n°5 is done.

Waste from recycling : $WasteCC_i = EWR \times QRP \times Inv_{i=5}$

The last category of emissions that needs to be taken into account is the emissions that arise from the disposal of a product at its end-of-life (EEOL). The quantity of products disposed of on a daily basis equals the daily demand minus the amount of products recovered, if investment n°5 is chosen.

End of life waste : $EOLCC_i = D \times EEOL - QRP \times EEOL \times Inv_{i=5}$

The yearly emissions have a much wider coverage than for the other models and are as follows :

$$YearlyEmissions_{i,p} = \left[\left(ManuCC_i + RecycleCC_i + TransCC_i + InputCC_i + PackCC_p + WasteCC_i + EOLCC_i\right) \times 310 + InvCC_i\right] \quad \forall\, i, \forall\, p$$

Objective function :

The objective function includes all operational costs and all emissions which are multiplied by the unique and deterministic carbon price, as follows :

$$minimize \left[\sum_{i=1}^{5}\sum_{p=1}^{3}\left(YearlyOpCosts_{i,p} + YearlyEmissions_{i,p} \times CarbonPrice\right)\right]$$

4.4 Results

4.4.1 Company A - EU ETS

Table 11 - Company A - Optimization results

	Low risk aversion		**Medium risk aversion**		**High risk aversion**	
	Investment(s) done	**Packaging chosen**	**Investment(s) done**	**Packaging chosen**	**Investment(s) done**	**Packaging chosen**

Scenarios 1-3	1-3-4-5	1	1-3-4-5	1	1-3-4-5	1
Scenarios 4-8	1-3-4-5	1	1-3-4-5	1	1-3-4-5	1
Scenarios 9-13	1-3-4-5	1	1-3-4-5	1	1-3-4-5	1

4.4.2 Company B - EU ETS & Luxemburg Carbon Tax

Table 12 - Company B - Optimization results

	Low risk aversion		**Medium risk aversion**		**High risk aversion**	
	Investment(s) done	**Packaging chosen**	**Investment(s) done**	**Packaging chosen**	**Investment(s) done**	**Packaging chosen**
Scenarios 1-3	1-5	1	1-5	1	1-5	1
Scenarios 4-8	1-5	1	1-5	1	1-5	1
Scenarios 9-13	1-5	1	1-5	1	1-5	1

4.4.3 Company C - California CaT

Table 13 - Company C - Optimization results

	Low risk aversion		**Medium risk aversion**		**High risk aversion**	
	Investment(s) done	**Packaging chosen**	**Investment(s) done**	**Packaging chosen**	**Investment(s) done**	**Packaging chosen**
Scenarios 1-3	1-5	1	1-5	1	1-5	1

Scenarios 4-8	1-5	1	1-5	1	1-5	1
Scenarios 9-13	1-5	1	1-5	1	1-5	1

4.4.4 Company D - Internal Carbon Pricing

Investment(s) done : 1-5

Packaging chosen : 1

5. Discussion

Before discussing the results of the different optimization models outlined above, it is important to remember that no precise insight can be drawn from the choice of investments alone. Although the carbon prices used in the models are realistic considering the knowledge gained from the literature review on the necessary carbon prices to reach the climate objectives of the Paris Agreement and knowing that their uncertainty of occurrence has been accounted for through stochastics, the models remain highly subjective. Indeed, the structural simplicity of the fictive supply chain used as well as the non-specificity of the parameter values, the amortization period and the interest rate of the loans chosen for this exercise make it inappropriate to reflect on the investment decisions alone. Hence, no extensive discussion will be held on the specific investment decisions that companies should take today to prepare for the future.

The main difference between companies A, B, C and D is the emissions coverage of the CPI in place in their location, making it difficult to compare their results. Company C, subject to the California CaT has a much wider coverage than Company A which needs to comply to the EU ETS. However, Company B, which, on top of the EU ETS, is subject to additional national taxes on fuel and construction because it has to comply with the Luxemburg regulations, has a similar coverage as Company C, but different carbon prices. The main point of comparability between the different companies is the fact that the carbon prices have been forecasted using the same method and that the stochastics have been conducted identically, which means that the results are obtained for the same time frame and for the same scenarios. Company D, however, is to be treated completely separately, as it is subject to a full emissions coverage, much wider than the other three companies, and is constructed as a deterministic optimization model, with only one expected carbon price and one time frame.

The two main variables that will be used for the discussion and, to the extent possible, comparing the results are the variables Inv_i and $Pack_p$. As a reminder, Inv_i is a binary variable indicating which investments are chosen, while $Pack_p$, also a binary variable, returns the type of packaging that is chosen.

Intuitively, it would make sense that, as the risk aversion level increases (which induces higher costs through higher disutility factors in the objective function), the companies are willing to spend more money on investments that will reduce their emissions and their operational costs so that their yearly costs are minimized. It would also make sense that, as the uncertainty of the future carbon market increases (which leads to a higher spread between the slopes of the forecasting graphs and thereby leads to a higher upper bound to which the highest disutility factor is associated), the company is willing to invest in abatement mechanisms that will reduce their emissions, carbon costs and overall operational costs. Unfortunately, these intuitions are not verified by the results. However, this does not mean that they are false, it might simply mean that the parameter values used in the models do not allow for these differences in reaction to be reflected in the results.

The results show a difference in investment decisions between company A and the other companies. Indeed, company A chooses to invest in all of the possibilities, except for investment n°2 (investing in energy-efficient machinery). Logically, and as enforced by the constraint, when investment n°1 (installing solar panels) is done, investment n°2 no longer is. The reason behind this is that, if consuming energy does not emit any emissions nor cost any money due to the solar panels, there is no interest for the companies to invest in new machinery that will release their electricity consumption. However, this is true in this case but would not necessarily be true if the cost of the investment in solar panels was made as to depend on the energy requirements. In that case, investment n°2 might be chosen in order to make investment n°1 more affordable and both investments would be chosen. Company A, as opposed to the other companies, invests in investments n°3 (building RDCs) and n°4 (purchasing electric vans). The possible reason behind this difference is that the emissions linked to the implementation of these investments are not taken into account in the scope of the EU ETS alone. Building RDCs and purchasing new vehicles thus does not increase the carbon budget of company A whereas it increases significantly the one of the other companies. This means that the costs of emissions linked to the construction of RDCs and purchase of new electric vehicles are higher than the costs of emissions linked to the transportation of products from the NDC to the SPs. A longer travelling distance or a raise in tax on fuel may thus easily change this result.

The two investments that are chosen in each scenario of each company are investments n°1 and investment n°5 (implementing a CLSCs). The installation of solar panels has a first obvious advantage of cutting down operational costs. Indeed, the energy consumption of the manufacturing process represents a high share of the daily costs and, if electricity no longer needs to be bought, it cuts down the daily costs significantly. On top of the reduction in operational costs induced by investment n°1, there are other significant advantages that arise from being energy-independent. The lack of carbon emissions linked to the electricity generation when using solar panels instead of grey electricity from the grid is surely one of them. Another advantage however has to do with the challenges of the energy transition. When phasing out of fossil fuels as primary energy sources, the electricity market suffers from increased intermittency linked to the use of renewable energy sources to produce electricity for the grid. Indeed, solar panels and wind turbines cannot respond to spontaneous increases in electricity demand like fossil fuels could, which could lead to potential shortages in electricity supply. Being energy-independent by investing in solar panels is thus an increased security for the long-term viability of the company.

Regarding investment n°5, which refers to the implementation of a closed-loop supply chain, the results indicate that it is always chosen along with investment n°1. Intuitively, if the company is energy independent and runs on green electricity, the operational costs of the CLSC are already significantly reduced, which encourages this investment. Moreover, investment n°5 allows the company to bring back old products into the value chain, which reduces the costs of new input. However, the fact that the emissions from the disposal of the products are not included in the emissions coverage of companies A, B and C is a disincentive for the implementation of a recovery loop, since the companies are not negatively affected by the disposal of their products at their-end-of-life. Then again, neither are the emissions that arise from the recycling process, which means that the reduction in operational costs from having to purchase less raw materials is the only incentive in this case. In the case of company D however, which has a full emissions coverage and thereby includes the emissions from waste generated if the products are simply disposed of at their end-of-life and from waste that occurs during the recycling process, the incentives for implementing a CLSC are lower. Still, investment n°5 is chosen but along with investment n°1, thanks to which the energy needs of the recycling loop are avoided. In reality, this is often the issue that companies who wish to improve their carbon footprint through the implementation of a CLSC encounter, as exposed in the literature review (see Section 2.3.1). Since scope 3 emissions (emissions from disposal of waste) are, in most cases, not included in the emissions coverage of the ICPs, recovering products for recycling and reuse only increases the total carbon budget of the companies, through the emissions that arise from the recycling process. In their paper, Fahimnia et al. (2013) suggest that “carbon costs incurred via reverse SC operations may need to be subsidized to a large extent by the governments in carbon pricing regulations”. Such a policy may indeed encourage companies to implement CLSCs despite the significant downside that they induce and adopt a circular approach to business. Circularity presents great environmental benefits, as it deals with the growing issue of resource scarcity (which is more pressing in certain industries than others). Maintaining and retaining the value of materials before they are downgraded is becoming primordial and will allow companies to persist in the long-term. Another great advantage of circularity is the financial resources that it offers, especially for Companies A and B which are located in the EU. The EU Taxonomy is gaining a lot of importance for the European companies, which have to start incroporating its requirements in their business model in order to, amongst other things, retain their investors. “Transition to a circular economy” being one of the six objectives of the system, CLSCs are becoming of critical importance. Implementing a CLSC might thus have negative financial repercussions in the short-term (if not subsidized by the governments, as suggested by Fahimnia et al. (2013)) but will most likely have more than compensating positive financial consequences in the long-term due to the influence of the EU Taxonomy on European companies.

The other decision variable that has not yet been discussed is the type of packaging chosen. The results of the optimizations indicate that, regardless of the time frame, degree of uncertainty of the carbon prices evolution and risk aversion level, the companies always choose to use packaging n°1 (packaging made out of PET). Although it is responsible for the most emissions, both during the production and the recycling, packaging n°1 is also the cheapest of the three options. Considering the fact that the CPIs of companies A, B and C do not cover these emissions, it makes sense that the cheapest packaging is chosen, regardless of the associated level of emissions. In the case of company D however, where the company’s policy includes the emissions of packaging in the coverage, a fair intuition would have been to expect packaging n°2 to be chosen, since cardboard induces less than nine times the amount of emissions as PET and only costs twice as much. Of course, this decision is highly dependent on the carbon price as well as the costs and emissions values associated to each packaging option which, once again, is highly subjective. The main insight to gain from this is that most companies today are subject to CPIs that do not take into account the emissions linked to their packaging, which explains why many of them still choose to use plastic packaging for its very low price, even though it is common knowledge that plastic is reponsible for higher levels of pollution and depend on non-renewable resources.

A final comment that should be made concerns the fact that, when an investment is implemented, the emissions linked to its implementation are all being faced by the company at once, which means that the costs of emissions are much higher for that year than they will be the following years. Since the model is only ran for one year, this likely dissuades the companies from investing and has an effect on the results. However, in reality, once an investment has been done, the benefits of its implementation last for many years. This means that investing in emissions abatement is even more profitable than it is portrayed to be in the models, if only the companies choose to have a longer-term approach. The results show that companies with a wider emissions coverage in the regulation tend to invest less in emissions abatement practices. Indeed, company A invests in investments n°3 and n°4 whereas all the other companies do not. This seems counter-intuitive at first, but it is most likely due to the issue of adopting a short-term view as the emissions induced by the investments will progressively be overcome by the cuts in emissions they allow for. This observation can be linked back to one of the main barriers to the implementation of green supply chain management practices exposed in Section 2.3.1. If firms adopt a short-term consideration of their financial performance, investing in emissions abatement or sustainable practices may seem non-profitable. However, if companies consider their long-term viability, they will quickly realize that these practices induce cost reductions and are primordial to their persistence.

6. Conclusion

The climate crisis is a complex and global issue that presents many uncertainties regarding its evolution and the ways to go about mitigating it. However, many negative consequences induced by its existence can already be experienced today and are evolving rapidly. Even though no specific plan of action has been mandated to slow the effects of climate change, objectives have been set by the Paris Agreement to limit global warming to well below 2°C compared to pre-industrial levels (United Nations, n.d.). The 196 parties present at COP21 ought to respect this engagement and many of them have implemented national or subnational regulatory systems to do so. Economic incentives, such as Emissions Trading Systems, Carbon Taxes, Internal Carbon Pricing and Carbon Offsetting are some of the main drivers for the transition towards green supply chain management, and have the advantage to be cost-effective due to the freedom that they give to the polluters to choose their method of emissions abatement (Meager et al., 2020 ; Kolstad, 2011). Carbon pricing instruments can vary immensely in terms of nature, object, outcome and viability depending on their macro-design (Pizarro, 2020). Their structure, as laid out throughout the literature review, has greatly evolved over time and will most likely continue to evolve in the future as to adapt to the climate needs. Historically, it can be seen that the emissions coverage of an instrument tends to grow over time, meaning that they are becoming increasingly constraining for the companies as they impact more and more parts of their value chain. Knowing that supply chains are often responsible for the majority of a company’s emissions, it is common for firms to implement green supply chain management practices in order to decarbonize their activities. However, because profitability remains central in our economy, the level of emissions abatement that is chosen by the companies will depend on the carbon prices that they are likely to be exposed to, since it directly affects their costs and thereby their profitability. The carbon markets around the world are evolving quickly and are expected to continue to do so in the upcoming years due to the urgency of the climate situation. The fact that the carbon prices will continue to increase is about certain, but how fast and by how much remains very uncertain. These uncertainties make it difficult for companies to take decisions today regarding the investments that should be made to lower their emissions and adequately prepare for the future.

This difficulty is precisely what was addressed by the optimization models presented in Section 4. Indeed, the models aimed to show the companies’ reactions when faced with different pricing scenarios linked to various degrees of uncertainty and presenting different levels of risk aversion to the evolution of the carbon market. The results do not allow for conclusions to be drawn on the differences in reactions of companies confronted to varying risk aversion levels or degrees of uncertainty. However, it can be seen that all companies decide to invest in several emissions abatement opportunities in order to adequately prepare for future rises in carbon prices and that the specificity of the chosen investments depends on the emissions coverage of each CPI.

On top of reducing the costs of the carbon emissions, investing in abatement mechanisms usually leads to cuts in operational costs too. This is one of the many drivers of implementing green supply chain management practices (Meager et al, 2020). Implementing a closed-loop supply chain also presents significant advantages and leads to operational costs reductions. This was demonstrated by the results of the optimization models, which show that investment n°5 was always amongst the most strategic investments to make. A circular business model allows for the value of the products to be retained in the value chain, which is of considerable importance given the increasing issue of resource scarcity and the rise in raw materials costs that it provokes. A reverse flow of products also allows the company to reduce their input costs, which is often a great financial advantage.

Energetical independence, or at least relying on electricity from renewable sources so as not to be impacted by the costs of the carbon emissions linked to consuming grey electricity, was also highlighted from the results as being an important element to face the challenges of increasing carbon prices in the future. There are very few companies today that do not have at least a small part of their activity which requires electricity. The future of our economy thus relies on the availability of electricity and, given the challenges that the electricity market faces while phasing out of fossil fuels, investing in renewable power sources seems like a reasonable investment to make to ensure the long-term profitability of the company.

Although no specific conclusions were able to be drawn from the optimization models, it is safe to state that investing in emissions abatement mechanisms as to decarbonize the supply chain is becoming increasingly important. Green supply chain management practices are thus central to mitigating climate change and should be used as a tool to reach the climate objectives. However, in order for a company to truly be sustainability-oriented, the core of the business model needs to change. This cannot be done by investing in just a few parts of the supply chain but involves a major redesign of the supply chain. The decisions of a truly sustainable firm, both short-term and long-term, are guided by sustainability. Internal Carbon Pricing is an instrument that is very useful to help companies keep their operations aligned with their sustainability objectives.

All the CPIs described in this thesis have their particularities, strengths and weaknesses. Their growing implementation across the world is driving companies to implement green supply chain management practices and abate their pollution levels. According to Nar (2020), using multiple CPIs simultaneously would lead to more effective climate mitigation, since they allow for a wider coverage of emissions. The scope of the CPIs will continue to increase in the next years, which will incentivize companies to invest in emissions abatement mechanisms as to increase the resiliency of their value chains and prepare for the threats and challenges brought by climate change. The climate crisis is changing the way business is conducted and companies need to embrace this opportunity to review the way they operate if they wish to perdure on the market.

7. Appendix

7.1 Carbon prices forecast – stochastics

Table 14 - EU ETS carbon prices (forecast table)

Timeline	Values	Forecast	Lower Confidence Bound	Upper Confidence Bound
01-10-18	$ 20.87			
01-01-19	$ 25.35			
01-04-19	$ 23.28			
01-07-19	$ 27.57			
01-10-19	$ 24.62			
01-01-20	$ 25.42			
01-04-20	$ 16.65			
01-07-20	$ 29.17			
01-10-20	$ 28.10			
01-01-21	$ 34.53			
01-04-21	$ 43.91			
01-07-21	$ 52.76			
01-10-21	$ 61.33			
01-01-22	$ 85.45			
01-04-22	$ 79.89	$ 79.89	$ 79.89	$ 79.89
01-07-22		$ 76.22	$ 54.46	$ 97.99
01-10-22		$ 80.32	$ 57.88	$ 102.75
01-01-23		$ 84.41	$ 61.31	$ 107.51
01-04-23		$ 88.50	$ 64.75	$ 112.25
01-07-23		$ 92.59	$ 68.21	$ 116.97
01-10-23		$ 96.68	$ 71.68	$ 121.69
01-01-24		$ 100.78	$ 75.16	$ 126.39
01-04-24		$ 104.87	$ 78.65	$ 131.09
01-07-24		$ 108.96	$ 82.15	$ 135.78
01-10-24		$ 113.05	$ 85.65	$ 140.45
01-01-25		$ 117.14	$ 89.17	$ 145.12
01-04-25		$ 121.24	$ 92.69	$ 149.79
01-07-25		$ 125.33	$ 96.22	$ 154.44
01-10-25		$ 129.42	$ 99.75	$ 159.09
01-01-26		$ 133.51	$ 103.29	$ 163.74
01-04-26		$ 137.61	$ 106.84	$ 168.37
01-07-26		$ 141.70	$ 110.39	$ 173.00
01-10-26		$ 145.79	$ 113.95	$ 177.63
01-01-27		$ 149.88	$ 117.51	$ 182.25

Table 15 - California CaT carbon prices (forecast table)

Timeline	Values	Forecast	Lower Confidence Bound	Upper Confidence Bound

01-07-17	$ -27.42			
01-10-17	$ -8.59			
01-01-18	$ -3.69			
01-04-18	$ -23.65			
01-07-18	$ -27.79			
01-10-18	$ -22.15			
01-01-19	$ -33.82			
01-04-19	$ 4.59			
01-07-19	$ -30.81			
01-10-19	$ -13.48			
01-01-20	$ -12.74			
01-04-20	$ -12.01			
01-07-20	$ -11.27			
01-10-20	$ 9.62			
01-01-21	$ 18.50			
01-04-21	$ 18.72			
01-07-21	$ 22.09			
01-10-21	$ 28.16			
01-01-22	$ 32.54			
01-04-22	$ 28.58	$ 28.58	$ 28.58	$ 28.58
01-07-22		$ 31.59	$ 5.60	$ 57.58
01-10-22		$ 34.51	$ 8.52	$ 60.51
01-01-23		$ 37.44	$ 11.44	$ 63.43
01-04-23		$ 40.36	$ 14.37	$ 66.35
01-07-23		$ 43.28	$ 17.29	$ 69.27
01-10-23		$ 46.20	$ 20.21	$ 72.20
01-01-24		$ 49.12	$ 23.13	$ 75.12
01-04-24		$ 52.05	$ 26.05	$ 78.04
01-07-24		$ 54.97	$ 28.97	$ 80.97
01-10-24		$ 57.89	$ 31.89	$ 83.89
01-01-25		$ 60.81	$ 34.81	$ 86.81
01-04-25		$ 63.73	$ 37.73	$ 89.74
01-07-25		$ 66.66	$ 40.65	$ 92.66
01-10-25		$ 69.58	$ 43.57	$ 95.59
01-01-26		$ 72.50	$ 46.49	$ 98.51
01-04-26		$ 75.42	$ 49.41	$ 101.44
01-07-26		$ 78.34	$ 52.33	$ 104.36
01-10-26		$ 81.27	$ 55.24	$ 107.29
01-01-27		$ 84.19	$ 58.16	$ 110.22

Table 16 - Slopes to 2030 forecasted prices

	Slope
EU ETS	To c1 = 11.285 To c2 = 14.888 To c3 = 18.491
California CaT	To c1 = 8.884 To c2 = 11.334 To c3 = 13.785

Table 17 - EU ETS : Slopes and forecasted prices for 2035

Slope evolution	Low uncertainty of carbon market evolution	High uncertainty of carbon market evolution
Increasing from c1	Slope = 14.888 Value in 2035 = USD 244.61	Slope = 18.491 Value in 2035 = USD 262.63
Stable from c1	Slope = 11.285 Value in 2035 = USD 226.60	Slope = 11.285 Value in 2035 = USD 226.60
Decreasing from c1	Slope = 7.682 Value in 2035 = USD 208.58	Slope = 4.079 Value in 2035 = USD 190.57
Increasing from c2	Slope = 18.491 Value in 2035 = USD 291.45	Slope = 22.094 Value in 2035 = USD 309.46
Stable from c2	Slope = 14.888 Value in 2035 = USD 273.43	Slope = 14.888 Value in 2035 = USD 273.43
Decreasing from c2	Slope = 11.285 Value in 2035 = USD 255.42	Slope = 7.682 Value in 2035 = USD 237.40
Increasing from c3	Slope = 22.094 Value in 2035 = USD 338.29	Slope = 25.697 Value in 2035 = USD 356.31
Stable from c3	Slope = 18.491 Value in 2035 = USD 320.28	Slope = 18.491 Value in 2035 = USD 320.28
Decreasing from c3	Slope = 14.888 Value in 2035 = USD 302.26	Slope = 11.285 Value in 2035 = USD 284.25

Table 18 - California CaT : Slopes and forecasted prices for 2035

Slope evolution	**Low uncertainty of carbon market evolution**	**High uncertainty of carbon market evolution**
Increasing from c1	Slope = 11.334 Value in 2035 = USD 156.32	Slope = Value in 2035 = USD
Stable from c1	Slope = 8.884 Value in 2035 = USD 144.07	Slope = 13.784 Value in 2035 = USD 168.57
Decreasing from c1	Slope = 6.434 Value in 2035 = USD 131.82	Slope = 8.884 Value in 2035 = USD 144.07
Increasing from c2	Slope = 13.784 Value in 2035 = USD 188.17	Slope = 3.984 Value in 2035 = USD 119.57
Stable from c2	Slope = 11.334 Value in 2035 = USD 175.92	Slope = 16.234 Value in 2035 = USD 200.42
Decreasing from c2	Slope = 8.884 Value in 2035 = USD 163.67	Slope = 11.334 Value in 2035 = USD 175.92
Increasing from c3	Slope = 16.235 Value in 2035 = USD 220.04	Slope = 6.434 Value in 2035 = USD 151.42
Stable from c3	Slope = 13.785 Value in 2035 = USD 207.79	Slope = 18.685 Value in 2035 = USD 232.39
Decreasing from c3	Slope = 11.335 Value in 2035 = USD 195.54	Slope = 13.785 Value in 2035 = USD 207.79

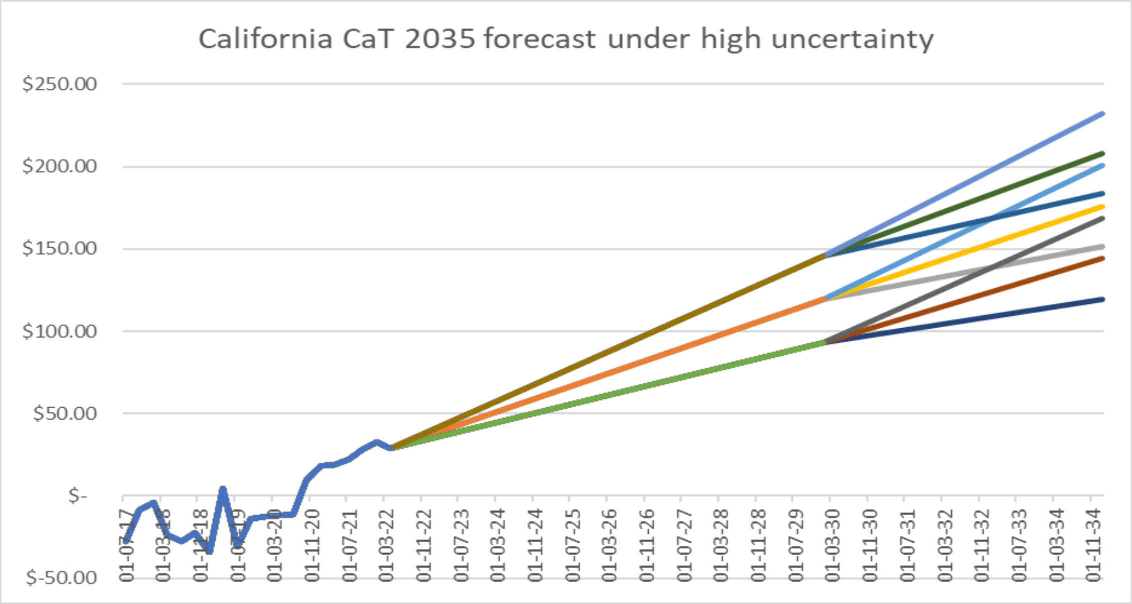


Figure 11 - California CaT 2035 forecast - high uncertainty

To calculate the disutility factor for each scenario and each risk aversion level, the ratio between the lowest carbon price (carbon price of s1) and the other carbon prices are first calculated. Then, they are used as *x*-values in the logarithmic function for each risk aversion level (see Table X below). Lastly, ratios are calculated between the obtained value of *f(x)* for the lowest carbon price (s1) and the other values of *f(x)*, giving the disutility factor for each scenario under each risk aversion level.

Table 19 - EU ETS - Calculation of disutility factor (scenarios 1-3)

	Scenario	**Carbon price (USD)**	**Carbon price ratio to s1**	***f(x)***	**Disutility factor (*f(x)* ratio to s1)**
Low risk aversion $f(x) = 2^x$	**s1**	170.17	1	2	1
	s2	198.99	1.17	2.25	1.125
	s3	227.82	1.34	2.53	1.266
Medium risk aversion $f(x) = 3^x$	**s1**	170.17	1	3	1
	s2	198.99	1.17	3.62	1.205
	s3	227.82	1.34	4.36	1.453

High risk aversion $f(x) = 4^x$	**s1**	170.17	1	4	1
	s2	198.99	1.17	5.06	1.266
	s3	227.82	1.34	6.41	1.602

Table 20 - EU ETS - Calculations of disutility factors (scenarios 4-8)

	Scenario	**Carbon price (USD)**	**Carbon price ratio to s1**	***f(x)***	**Disutility factor (*f(x)* ratio to s4)**
Low risk aversion $f(x) = 2^x$	**s4**	219.39	1	2	1
	s5	241.14	1.10	2.14	1.071
	s6	273.43	1.25	2.37	1.186
	s7	305.86	1.39	2.63	1.314
	s8	327.48	1.49	2.81	1.407
Medium risk aversion $f(x) = 3^x$	**s4**	219.39	1	3	1
	s5	241.14	1.10	3.35	1.115
	s6	273.43	1.25	3.93	1.311
	s7	305.86	1.39	4.63	1.542
	s8	327.48	1.49	5.15	1.718
High risk aversion $f(x) = 4^x$	**s4**	219.39	1	4	1
	s5	241.14	1.10	4.59	1.147
	s6	273.43	1.25	5.63	1.407
	s7	305.86	1.39	6.91	1.727
	s8	327.48	1.49	7.92	1.980

Table 21 - EU ETS - Calculations of disutility factors (scenarios 9-13)

	Scenario	**Carbon price (USD)**	**Carbon price ratio to s1**	***f(x)***	**Disutility factor (*f(x)* ratio to s9)**
Low risk aversion $f(x) = 2^x$	**s9**	204.38	1	2	1
	s10	232	1.14	2.20	1.098
	s11	273.43	1.34	2.53	1.264
	s12	314.48	1.54	2.91	1.453
	s13	342.48	1.68	3.19	1.597
Medium risk aversion $f(x) = 3^x$	**s9**	204.38	1	3	1
	s10	232	1.14	3.48	1.160
	s11	273.43	1.34	4.35	1.449
	s12	314.48	1.54	5.42	1.807
	s13	342.48	1.68	6.30	2.101
High risk aversion $f(x) = 4^x$	**s9**	204.38	1	4	1
	s10	232	1.14	4.82	1.206
	s11	273.43	1.34	6.39	1.597
	s12	314.48	1.54	8.44	2.110
	s13	342.48	1.68	10.21	2.552

Table 22 - California CaT - Calculations of disutility factors (scenarios 1-3)

	Scenario	**Carbon price (USD)**	**Carbon price ratio to s1**	***f(x)***	**Disutility factor (*f(x)* ratio to s1)**
Low risk	**s1**	99.65	1	2	1

aversion $f(x) = 2^x$	**s2**	119.25	1.20	2.29	1.146
	s3	138.86	1.39	2.63	1.314
Medium risk aversion $f(x) = 3^x$	**s1**	99.65	1	3	1
	s2	119.25	1.20	3.72	1.241
	s3	138.86	1.39	4.62	1.541
High risk aversion $f(x) = 4^x$	**s1**	99.65	1	4	1
	s2	119.25	1.20	5.25	1.313
	s3	138.86	1.39	6.90	1.725

Table 23 - California CaT - Calculations of disutility factors (scenario 4-8)

	Scenario	**Carbon price (USD)**	**Carbon price ratio to s1**	***f(x)***	**Disutility factor (*f(x)* ratio to s4)**
Low risk aversion $f(x) = 2^x$	**s4**	139.17	1	2	1
	s5	153.80	1.11	2.15	1.076
	s6	175.92	1.26	2.40	1.201
	s7	197.97	1.42	2.68	1.340
	s8	212.65	1.53	2.88	1.442
Medium risk aversion $f(x) = 3^x$	**s4**	139.17	1	3	1
	s5	153.80	1.11	3.37	1.122
	s6	175.92	1.26	4.01	1.337
	s7	197.97	1.42	4.77	1.591
	s8	212.65	1.53	5.36	1.786
High risk	**s4**	139.17	1	4	1

aversion $f(x) = 4^x$	**s5**	153.80	1.11	4.63	1.157
	s6	175.92	1.26	5.77	1.442
	s7	197.97	1.42	7.19	1.796
	s8	212.65	1.53	8.32	2.079

Table 24 - California CaT - Calculations of disutility factors (scenarios 9-13)

	Scenario	**Carbon price (USD)**	**Carbon price ratio to s1**	***f(x)***	**Disutility factor (*f(x)* ratio to s9)**
Low risk aversion $f(x) = 2^x$	**s9**	128.96	1	2	1
	s10	147.75	1.15	2.21	1.106
	s11	175.92	1.36	2.57	1.287
	s12	204.22	1.58	3	1.499
	s13	223	1.73	3.32	1.658
Medium risk aversion $f(x) = 3^x$	**s9**	128.96	1	3	1
	s10	147.75	1.15	3.52	1.174
	s11	175.92	1.36	4.48	1.492
	s12	204.22	1.58	5.70	1.899
	s13	223	1.73	6.68	2.228
High risk aversion $f(x) = 4^x$	**s9**	128.96	1	4	1
	s10	147.75	1.15	4.90	1.224
	s11	175.92	1.36	6.63	1.657
	s12	204.22	1.58	8.98	2.246
	s13	223	1.73	10.99	2.748

7.2 Models parameter values

Table 25 - Reference values for calculation of parameters

Truck fuel consumption	20L diesel / 100 km
Emissions of diesel	2.64 kg CO2e/L
Price of electricity form grid	USD 0.2/kWh
Electricity consumption before investment n°2	2500 kWh
Electricity consumption after investment n°2	1655 kWh
Emissions from grey electricity	0.2 kgCO2e / kWh
Emissions from disposal of packaging (incineration)	PET : 2139 kgCO2e / ton of waste Cardboard : 120 kgCO2e / ton of waste Bioplastic : 2000 kfCO2e / ton of waste
Emissions from production of packaging	PET : 3.271 kgCO2e / kg Cardboard : 0.39 kgCO2e / kg Bioplastic 2.82 kgCO2e/kg
Weight of single packaging	PET : 10 g Cardboard : 15 g Bioplastic : 10 g
Emissions from the production of solar panels	64.6 gCO2e / kWh produced
Emissions from the purchase of new machinery (production of machine)	3 000 kgCO2e
Monetary emissions factor (from building)	150 kgCO2e / k €
Emissions from the purchase of a new vehicle (production)	20 tCO2e

Electricity consumption of recovery loop	500 kWh

Table 26 - Parameter values

Parameter	**Unit**	**Value**
Demand (D)	Units of product	10 000 / day
Cost of one unit of input (CI)	USD	10
Emissions of one unit of input (EI)	kgCO2e	2
Daily emissions of manufacturing process from energy consumption before investment n°2 (EMI)	kgCO2e	500
Reduction in daily emissions of manufacturing process in energy consumption after investment n°2 (EMF)	kgCO2e	325
Emissions linked to the manufacturing of one unit of product (EMP)	kgCO2e	0.5
Daily cost of manufacturing process from energy consumption before investment n°2 (CMI)	USD	500
Reduction in daily cost of manufacturing process in energy consumption after investment n°2 (CMF)	USD	325
Cost of packaging for one unit of product (CPack)	USD	p1 : 0.05 p2 : 0.10 p3 : 0.07
Emissions from packaging for one unit of product (EPack)	kgCO2e	p1 : 0.0541 p2 : 0.0057 p3 : 0.0482
Yearly cost of implementing investments (CInv)	USD	i1 : 44 000 i2 : 8 800 i3 : 88 000 i4 : 52 800 i5 : 15 400

Emissions linked to the implementation of investments (EInv)	kgCO2e	i1 : 193.80 i2 : 3 000 i3 : 144 000 i4 : 60 000 i5 : 3 000
Daily transport distance before investment n°3 (DI)	km	1 000
Reduction in daily transport distance after investment n°3 (DF)	km	250
Cost of diesel fuel (CF)	USD/km	0.36
Emissions from diesel fuel usage (EF)	kgCO2e/km	0.528
Daily cost of the recycling process from energy consumption (CR)	USD	100
Emissions from the energy consumption of the recycling process (ER)	kgCO2e	100
Emissions linked to the recycling process of one unit of product (ERP)	kgCO2e	0.15
Emissions linked to the disposal of one unit of product (EEOL)	kgCO2e	2
Emissions linked to waste through the recycling of one product (EWR)	kgCO2e	0.3
Quantity of products recovered daily (QRP)	Units of products	100
Quantity of input recovered daily (QRI)	Units of input	50

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