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The Structural Determinants of Carbon Prices in the EU-ETS

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"On croit que l'homme peut s'en aller droit devant soi. On croit que l'homme est libre... On ne voit pas la corde qui le rattache au puits, qui le rattache, comme un cordon ombilical, au ventre de la terre. S'il fait un pas de plus, il meurt."

Antoine de Saint Exupéry, Terre des Hommes

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Résumé

Les déterminants structurels du prix du carbone sur le Système d'Echange de Quotas d'Emission européen

Le marché européen du carbone (SEQE) est défini comme la pierre angulaire de la politique climatique européenne. Cependant, sa capacité à placer durablement l'économie sur une trajectoire bas carbone demeure incertaine. Les niveaux de prix du carbone ont longtemps été jugés trop bas, et sa trajectoire trop volatile, pour déclencher les investissements nécessaires à une décarbonation de l'industrie et à l'abandon définitif des énergies fossiles. L'évolution des prix observés par le passé a largement été attribuée à un déséquilibre de l'offre de permis, dû à des chocs externes au marché. Ainsi, plusieurs mesures de restriction de l'offre, critiquées dans un premier chapitre, furent entreprises afin d'en préserver le SEQE, sans rencontrer le succès escompté.

Toutefois, la plupart des analyses prospectives du SEQE reposent sur un modèle archétypal d'échange de permis à polluer, qui ne tient compte ni de la structure interne du marché ni de ses fondamentaux. Cette thèse a ainsi pour but d'indentifier les déterminants structurels du prix du carbone sur le SEQE, ainsi que d'en évaluer l'impact sur l'équilibre de marché et la conception de politiques de l'offre. Motivés par l'examen de données microéconomiques de transaction et d'émission, les second et troisième chapitres conduisent l'analyse *ex-post* des Phases 2 (2008-2012) et 3 (2013-2020) du mécanisme. Ils mettent ainsi en lumière la nature instable de la structure interne du marché. Nos résultats suggèrent notamment que les coûts de transaction altȓent la flexibilité spatiale du SEQE, tandis que le progrès technologique déstabilise le plafond d'émission.

Ces constats nous amènent ainsi à considérer un prix plancher du carbone, pour remédier à ces instabilités. La réserve de stabilité du marché mise en place en 2019 a en effet été critiquée pour l'incertitude supplémentaire qu'elle génère. Un quatrième chapitre mène donc l'analyse *ex-ante* du secteur électrique du SEQE en présence de trois types de prix plancher différents. Nos résultats suggèrent que la capacité de la MSR à rapidement réduire le nombre de permis en circulation ne justifie pas la mise en oeuvre d'un mécanimse de support du prix à court terme. Rétablir rapidement la rareté des quotas est en effet crucial dans le SEQE, où le surplus de permis actuel est important.

Mots clés : SEQE, marchés carbone, politique climatique, microéconomie appliquée, comportement des firmes, analyse empirique

Abstract

The structural determinants of carbon prices in the EU-ETS

The European Union Emissions Trading Scheme (EU-ETS) is referred to as the cornerstone of the EU's fight against climate change. However, its ability to durably put the economy on a low-carbon path and eventually reach long-term climate targets has been questioned. Carbon prices delivered have been judged too low and volatile to trigger the necessary investments in a cleaner production, and permanently phase out fossil fuels indeed. Price outcomes were largely attributed to a supply imbalance of permits due to external shocks: supply-side reforms, critically reviewed in a first chapter, were in turn conducted to shield the EU-ETS from them, with limited success.

Yet, most prospective analyses of the EU-ETS rest on archetypal models of emission trading, which disregard its market structure. Therefore, this dissertation contributes to better understand price formation in the European carbon market by investigating structural drivers of permit prices, appraising their impact on market outcomes and policy design. Motivated by transaction and compliance data, the second and third chapters provide *ex-post* analyses of the second (2008-2012) and third (2013-2020) trading periods. We find that the market structure is unstable, both in its static and dynamic dimensions, with consequences on prices and supply-side policies. Specifically, trading costs impact firms' trading decisions and static efficiency of the market. Technological progress also alters the effective ceiling over-time by changing plants' baseline emissions.

These results question the benefits of a carbon price floor to remedy these instabilities, by helping market actors anchor expectations about future carbon prices. The market stability reserve implemented in 2019 may indeed create another layer of uncertainty in an already complex regulatory environment. A fourth chapter thus conducts a comparative *ex-ante* analysis of the EU-ETS power sector under the *status quo* or three plausible price floor policies. Our results suggest that no such complementary policies are necessary, because of the MSR's ability to quickly cutback on the number of allowances in circulation. Indeed, our analysis suggests restoring the short-term permit scarcity of permits in decisive in the EU-ETS, where the current excess supply is large.

Key words : EU-ETS, carbon markets, climate policy, applied microeconomics, firm behavior, empirical analysis

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General Introduction

In December 2019, European Commission president Ursula Von Der Leyen gave a fervent speech in front of the European parliament to present the *European Green Deal*. The deal set the goal of reaching climate neutrality by 2050, in order to spark the transition to a low carbon economy. In her words, «*It will set clear rules, so that investors and innovators can plan their long-term investment. It will make the transition towards climate neutrality accountable and reliable. And next summer, we will present a plan [the climate law, ed] to increase our ambition in cutting emissions.*». Although the terminology is new, the method is not. To realize its intentions, the European commission primarily relies on an 50-year-old mechanism indeed: emissions trading. Fifteen years ago, the Kyoto protocol led the EU to implement an emissions trading scheme (ETS) of its own, the EU-ETS, designated chief instrument for the community's climate policy. However, the EU-ETS rapidly endured lively criticism. Although the mechanism demonstrated that emissions trading can work and generate a carbon price, the low and volatile prices it delivered in the second (2008-12) and early third (2013-2020) trading periods were not perceived as *game changers* indeed. To remedy these issues, supply-side reforms were undertaken in turn, in the form of auction deferments and a market stability reserve. Yet, reforms have only partly fulfilled their support and stability functions, questioning the capacity of the EU-ETS to durably put the economy on a low-carbon path.

In our view, these shortcomings question the applicability of the seminal models of emissions trading, namely the works of Montgomery, 1972 and Rubin, 1996, to represent the functioning of the market in practice, and design supply-side reforms. In particular, these models, which still serve as a basis for most policy simulations in the EU-ETS, rule out market structure as a determinant of price formation. By contrast, we argue in this dissertation that micro-economic decisions can, by reshaping market fundamentals and its inner structure in turn, alter both its static and dynamic efficiency, with consequences on the European carbon price and policy design. This dissertation thus conducts *ex-post* analyses of the EU-ETS relying on transaction and compliance data, in order to identify the determinants of carbon price formation which relate to changes in the internal market structure. Results then serve as a basis for *ex-ante* policy simulations, which help us elaborate policy recommendations to improve the EU-ETS' economic and environmental effectiveness.

Origins of climate science and global climate policies

The greenhouse-gas effect finds its origins in the 19th century, in the work of Tyndall, 1859. Tyndall experimented the idea of Joseph Fourier formulated 30 years before, and established for the first time that molecules of gases, such as water vapour, carbon dioxide and methane, absorb more energy than oxygen and nitrogen when radiant heat is passed through them. A link with climate change was already made explicit then, the scientist's declaration shows: «*The bearing of this experiment upon the action of planetary atmospheres is obvious... the atmosphere admits of the entrance of the solar heat, but checks its exit; and the result is a tendency to accumulate heat at the surface of the planet*». Tyndall's work led Svante Arrhenius, in 1896, to first calculate the extent to which mean temperatures of the ground are influenced by the presence of carbon dioxide (CO_2) in the atmosphere (Arrhenius, 1896). His work led him to conclude that industrial emissions are too large to be compensated by natural carbon sink, hence generating global warming.

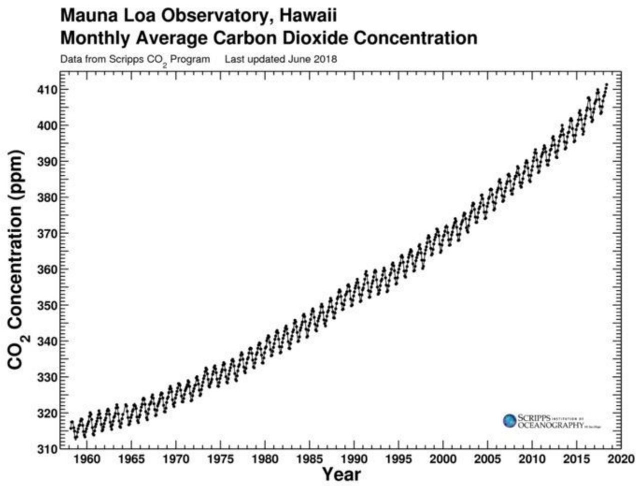
Fast-forwarding a hundred years later brings us to 1958. Benefiting from advances in measurement techniques, Charles Keeling, who had collected atmospheric data in Antarctica and Mauna Loa, Hawaii, first confirmed that concentration levels of CO_2 were rising (Keeling, 1958). His data, represented in the Keeling curve (figure 1), became an icon of the greenhouse effect for both scientists and the public opinion. In the following decade, technological advances in weather measurement by satellites fed the climate change research, providing solid evidence of an early global warming.[1] In 1968, a group of scientists, politicians, diplomats and business leaders created a group, known as the *Club of Rome*, to tackle the global problems of mankind. In a famous report by Meadows et al., 1972, and better know as «*The Limits to Growth*», a group of MIT researchers proposed, on behalf of the Club, a prospective modeling of a global system described by five variables interacting with each-other: population increase, agricultural production, nonrenewable resource depletion, industrial output, and pollution generation. Their results emphasized the unsustainable nature of the economic system in a world of limited resources, which found a high resonance in the international community.

Moreover, the context of space exploration and the publication of the first clichés of the earth from lunar orbit, favored a growing consciousness and concern for environmental conservation and resource depletion. Two books resonated in the public opinion: Rachel Carson's bestseller «*Silent Spring*» in 1962, and «*The Population Bomb*» by Paul R. Ehrlich, which brought the issue of natural resource overuse and the links between pollution and public health to the public. Inspired by student anti-war movements, the

[1] TIROS (Television Infrared Observation Satellite) of NASA was the first operational weather satellite.

first «Earth Day» took place in 1970, thus giving a political influence to environmentalists. The demonstration led to creation of the United States Environmental Protection Agency (EPA) the same year, and the enactment of the Clean Air Act, considered to be the first large-scale environmental policy to limit emissions from industrial and mobile sources.

FIGURE 1: Keeling Curve



Note: The Keeling curve represents Keeling's data since 1958, which scientists have continued to collect since his death in 2005.

It is only a decade later, in 1988, that international cooperation took up the issue of climate change. The United Nation and World Meteorological Organization created an Intergovernmental panel on Climate Change (IPCC, or *GIEC* in french), composed by thousands of scientists, to provide policymakers with a scientific, peer-reviewed expertise on the current state of knowledge about climate change, its social and economic impacts, and possible adaptation strategies. In a first report published in 1990, the IPCC confirmed the anthropogenic source of the greenhouse-gas effect and global warming due to CO_2 emissions, and portrayed a grim future if no change was to be made. For instance, the baseline scenario, i.e. with no mitigation measures, resulted in an increase in temperature by 3°C by 2100, with a 65cm rise in sea levels and severe consequences on agriculture, biodiversity, water resources and economic activity in vulnerable regions[2]. The first IPCC report thus served as a basis for the United Nations Framework Convention of Climate Change (UNFCCC), ratified by 154 countries at the Earth Summit in 1992.

The main objective of the UNFCCC is *«to stabilize greenhouse gas concentrations in the atmosphere at a level that will prevent dangerous human interference with the climate system»*,

[2]See the executive summary of the first and second IPCC reports at : https://www.ipcc.ch/site/assets/uploads/2018/05/ipcc_90_92_assessments_far_full_report_fr.pdf

and it remains the backbone of international climate negotiation. Parties of the convention have met in annual Conference of Parties (COP) to assess progress in climate change mitigation, one of the most important being the 21st, which led to the Paris agreement in 2015. The UNFCCC also led to ratify the Kyoto protocol, which established legally-binding emissions regulations that are still in force, including the EU-ETS.

Brief history of environmental economics and carbon pricing

Increasing air pollution in developed countries, due to road transport and industrial plants, and a growing environmental consciousness in the public opinion and the political space led the environmental economics field to naturally emerge in the 1960s. Central to this discipline is the concept of non-excludable goods (i.e. individuals cannot be excluded from use), including public and common goods. The theory of public goods, which are also non-rivalrous (i.e. where use by one individual does not reduce availability to others) is first attributed to Samuelson, 1954. Paul Samuelson demonstrated that in the presence of a public good, like education or national defense, the private market is not likely to result in an efficient production because individual, gain-maximizing decisions do not account for its social benefits, or externalities. Therefore, the government should provide the public good by requiring users to pay their fair share through taxes, or it will otherwise be under-produced, overused or degraded. This type of market failure leads to the well-known ’free-rider’ problem, when users of the public good freely benefit from its production, without contributing to its maintenance.

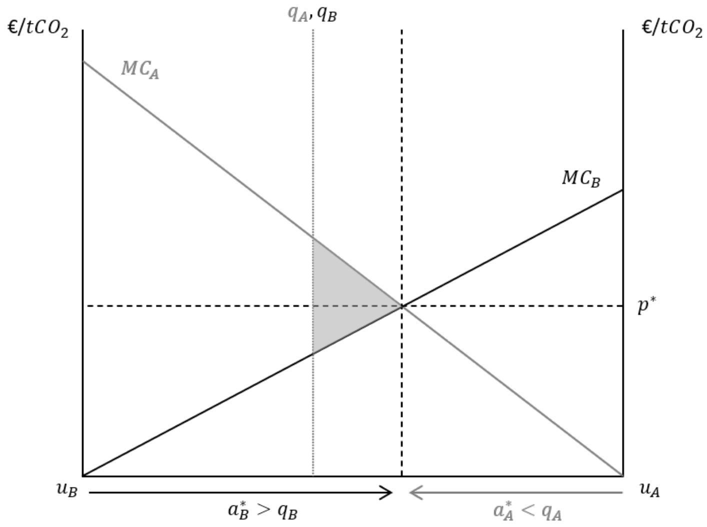
Like public goods, common goods face an externality problem with the difference that it results in reducing the availability (or the quality) of the good to others users. In other words, a common good is rivalrous and as such, private decisions will result in over-exploiting or degrading it, since they do not take into account users’ rivalry. This phenomenon leads to the famous *tragedy of the commons* when individual consumers behave contrary to the common good of all consumers by spoiling the shared resource through their collective action. Hardin, 1968 described how a common-access pasture would degrade as each individual herder seeks to improve their own outcome by increasing their own sheep numbers, while the common pasture becomes overgrazed. The earth’s atmosphere is also an example of a common good, more precisely a ’global environmental common’ (Brousseau et al., 2012) since it is shared by everyone on earth, with rivalry of use yet: the air that I breathe is no longer available to my neighbor. As such, it is also subject to a market failure by definition. More precisely, industrial activities relying on the combustion of fossil fuels have individually grown according to profit maximizing decisions, gradually leading to the stock of CO_2 accumulating in the atmosphere, and global warming.

The issue of externalities characteristic of non-exludable goods was tackled early by Pigou, 1920, whose work remains central to modern environmental economics. Pigou argued that market failures can be corrected by imposing an eponymous tax (or subsidy) amounting to the marginal damage (or benefit) associated with the use, or production of the good. In the context of a global common like the earth's atmosphere, a Pigouvian tax imposed on the marginal damage associated with polluting carbon dioxide (CO_2) emitted by the industry should therefore restore a first best pollution outcome. This mechanism is also known as the 'polluteur-pays' principle. Yet, and precursor to the theory of carbon markets, Coase, 1960 argued that government intervention is not even necessary. When two polluters compete for access to a resource, a first best allocation can also be attained by simply defining property rights. Indeed, in the absence of transaction costs, Coase showed that bargaining between rivals will lead to an efficient pollution outcomes, as polluters will naturally agree on a fair compensation for the damage they impose on each other.

Thus, market-based environmental instruments were already in gestation in the second half of the XXth century. However, the materialization of Pigou or Coases' theories came up against a substantial problem in practice: how can a regulator measure the social marginal cost associated with air pollution, or ensure compliance with property rights on such intangible goods like air ? The design of a first best policy being impracticable in the context of global warming, economists starting to think in a logic of second best, which led to the emergence of carbon markets. More precisely, Crocker, 1966b and Dales, 1968a outlined a mechanism of quantity pollution control, in the form of tradeable pollution licenses, or permits. Formalized a few years later by Montgomery, 1972, carbon markets have several advantages: (i) they enable governments to have control over the total quantity of carbon emitted in the atmosphere, which suits well the issue of climate change, (ii) in second best, they lead to an economically efficient pollution outcome thanks to permit trading and (iii) regardless of the initial allocation of permits (i.e. the independence of initial allocation property). Specifically, these outcomes rest on the so-called equi-marginal value principle in equilibrium, which state that cost-minimizing emission levels are such as the marginal marginal abatement costs of polluters are equal.

Figure 2 illustrates the static equilibrium outcomes of a market for pollution rights with two polluters A and B, with high and low marginal abatement costs, respectively. Both polluters receive an initial permit endowment denoted q_A and q_B, which, before trading, constraints A (resp. B) to reduce its emissions by $u_A - q_A$ (resp. $u_B - q_B$), where u_A and u_B denote $laisser faire$ emissions of A and B. In equilibrium, abatement outcomes are such that marginal abatement costs of A and B are equal, revealing the market price of

FIGURE 2: Cap-and-trade scheme with two polluters



carbon $p^\star$. More precisely, permit trading results in the low-abatement-cost polluter B to abate more than its initial permit allocation ($a_B^\star > q_B$) and sell its extra permits at price $p^\star$ to the high-abatement cost polluter A. The transaction allows polluter A to avoid costly abatement and buy permits from B to cover its emissions instead ($a_A^\star < q_A$). Therefore, gains from trade between B and A are represented by the grey shaded area.

Economists have widely agreed that marketable emission permits can be a cost-effective strategy to control air pollution. By contrast to command-and-control instruments, which were prevalent in the 60s, emissions trading schemes (ETS) provide two sources of cost-savings for regulated plants. As discussed above, the first source of flexibility stems from spatial emissions trading. The equi-marginal value principle states that, as a result of permit exchange, any distribution of permits among polluters should result in an efficient allocation of abatement efforts indeed. In other words, the market ensures that abatement happens where it is the cheapest: hence, the perimeter of the market can cover heterogeneous economic sectors and countries. This aspect of ETS is convenient for the regulator in absence of information about private costs, since does not have to arbitrarily pick a value for the carbon externality. Moreover, an ETS is more politically appealing than a tax on emissions, which can be perceived punitive to regulated plants (Ellerman and Buchner, 2007).

Second, markets for pollution rights enable regulated entities to trade permits through time, which constitutes the second and major source of flexibility of ETS. Plants have typically been allowed to put unused permits in a personal reserve for future use, and borrow extra allowances from future allocation. The Acid Rain program, which was the first ETS to ever be implemented under the Clean Air Act amendments of 1990, included the so-called *banking* and *borrowing* provisions. However, and although a temporal flexibility existed in the first ETS, the theoretical analysis of inter-temporal emissions trading only emerged a few years later in the seminal work of Rubin, 1996. Importantly, Rubin found that inter-temporal permit trading improves the efficiency of permit market, by allowing regulated plants to shift their emissions stream through time. In particular, economic efficiency requires to build a permit bank at the beginning of the trading period, and gradually use it to cover emissions as the resource (pollution permits) become scarcer and more expensive – hence the characteristic bell shape of the permit bank. Importantly, and provided that the permit and output markets are competitive, the price path of allowances then follows Hotelling's rule for extraction of exhaustible resources and grows at the exogenous rate of return in absence of banking and borrowing constraints (Hotelling, 1931).

Montgomery and Rubin's results served as a basis for subsequent research on carbon markets, and are still relevant in the majority of today's models, including the EU-ETS's. In the years that followed, theoretical work first consisted in incorporating market imperfections or behavioral biases in the founding model, initiating branches in the literature on permit markets. Hahn, 1984 first analyzed the issue of market power in the permit market, followed by Eshel, 2005 in the goods market. Montero, 1998 and Schennach, 2000 also provided the first analytical treatments of uncertainty in permit markets. Finally, Stavins, 1995 studied the issue of transaction costs in the seminal model, relaxing Coases' assumptions. This dissertation finds its roots in the founding models of permit markets as well (Montgomery, 1972; Rubin, 1996). Yet, each chapter develops and builds on a particular branch of the literature departing from the seminal models, which will be developed in the main text. For instance, chapter 2 focuses on the issue of transaction costs while chapter 3 contributes to the induced technological change literature. Finally, chapter 4 contributes to the famous «price vs. quantities» debate (Weitzman, 1974) in the context of permit markets.

The EU-ETS: from theory to practice

Since the Acid Rain Program of 1990, carbon markets have grown in number and importance, and now play an essential role in the global fight against climate change. As of 2020, national or sub-national systems are already operating or under development in Canada, China (seven regional pilots), Japan, New Zealand, South Korea, Switzerland and the United States (California cap-and-trade, Regional Greenhouse-Gas Initiative). Yet, the European-Union Emissions Trading Scheme (EU-ETS) remains the largest carbon market worldwide. Chapter 1 provides an overview of the origins of the european carbon market, and the crises and reforms it has faced since its implementation to this day.

Conceived within the framework of the Kyoto protocol, the EU-ETS was conceived for purposes of (i) securing the environmental commitments of EU member states vis-à-vis the Kyoto Protocol, and (ii) affirming Europe's leading role in climate change policy (Convery, 2009). It was officially launched in 2005 for a three-year pilot phase, to prepare for the first Kyoto commitment period in 2008. The strength of the mechanism rests in its large geographical and industrial coverage, since it includes every industrial plant or power station with a net heat excess of 20 megawatt. This represents about 45% of greenhouse-gas emissions in 31 countries of the European Community. At its debuts, the EU-ETS was hailed as the successful application of the emissions trading's founding models to a real-world situation. Indeed, it demonstrated that creating a large-scale regulation of greenhouse-gas emissions based on the principles of tradable pollution rights, namely (i) a declining emission ceiling, (ii) a yearly allocation of permits and (iii) a monitoring, reporting and verification system, is feasible in practice. Second, it successfully generated a carbon price *ex-nihilo*.

However, the days of glory of the EU-ETS did not last long. In its second phase (2008-2012), it received very bad press indeed, mainly for the low price levels it delivered. Despite the increasing trading volumes and a promising kick-off at 25-30€/tCO_2, prices sharply declined in mid-2008 to 15€/tCO_2, and settled around 5-10€/tCO_2 until the end of Phase 3 (2019). Despite its good environmental performances (emission milestones have always been reached in advance[3]), the EU-ETS has essentially been evaluated on the basis of carbon prices it generated. In fact, expectations about the mechanism go beyond a mere price discovery function usually promoted by economists, and are rather concerned with the unstated, political goals of the EU-ETS. First, driving low-carbon investment in the long-run and second, promoting the EU as a pioneer in climate action. As a result, environmental advocates anchored their expectations in existing carbon values, like the tutelary value of carbon or existing carbon taxes.[4] Higher in value, these reference prices dampened the credibility and ambition of the EU-ETS in turn. Moreover, the generous free allocation of permits to installations raised doubts about the ability of the mechanism to implement the polluter-pays principle. Important windfall profits could have benefited industrial polluters indeed.

The 2009 price slump, and the rather erratic variation of carbon prices sparked an abundant empirical literature on the carbon price determinants in the EU-ETS. Econometric

[3] https://ec.europa.eu/clima/policies/ets_en

[4] For instance, the French carbon price used to guide public spending amounts to 90€/tCO_2 in 2020 (Quinet, 2012), the 2030 goal price recommended in the High-Level Commission on Carbon Prices to 100€/tCO_2 (Stiglitz et al., 2017) and the Swedish carbon tax to 100€/tCO_2 in 2020

studies found European Union Allowances (EUA) to be driven by energy prices (Creti, Jouvet, and Mignon, 2012; Koch et al., 2014), renewable energy supply and weather variation (Alberola, Chevallier, and Chèze, 2008; Rickels, Görlich, and Peterson, 2015), political events and announcements (Hitzemann, Uhrig-Homburg, and Ehrhart, 2015; Koch et al., 2016), banking of allowances (Hintermann, 2010), or hedging and speculation (Friedrich et al., 2020).[5] Besides, the price drop observed in 2009 was largely attributed to a hefty supply imbalance of permits due to three factors. First, the long-lasting economic downturn that followed the financial crisis, which caused production and emission to slow-down. Second, the presence of unilateral overlapping environmental policies like the support to renewable energy sources, that structurally reduced the demand for allowances (De Perthuis and Trotignon, 2014). Third, the massive use of international credits (CER/ERU) in place of EUAs to cover emissions (Ellerman, Valero, and Zaklan, 2015).

So far, reasons invoked for the price path to depart from the Hotelling rule have been external to the carbon market, whether structural or economic. As such, reforms undertaken to (i) fix the supply imbalance and address the supply-side rigidity of the EU-ETS, and (ii) raise and stabilize EUA prices, followed Rubin's logic. In other words, they were built on the assumption that carbon prices are primarily determined by the stringency of the emission ceiling. Two main reforms took place in the third trading period (2013-2020) indeed. Firstly, a decision was made to postpone the auctioning of 900 million allowances in order to manage the large permit surplus accumulated over the second trading period. The «back-loading» procedure froze 400 million allowances in 2014, 300 million in 2015 and 200 million in 2016. Second, and more importantly, the European Commission implemented a Market Stability Reserve (MSR) in 2019, which behaves like a quasi-automatic stabilizer which controls the volume of allowances in circulation (TNAC). Specifically, the MSR withdraws (adds up) allowances to auction if the TNAC exceeds (falls under) a certain threshold.

Although Phase 3 reforms have succeeded in raising EUA prices on average, they have not managed to stabilize them. In turn, the adequacy of the MSR to fix the EU-ETS has been questioned in the literature. The MSR has been indeed criticized to generate price volatility by adding uncertainty to an already complex regulation (Richstein, Chappin, and Vries, 2015). Moreover, a price/quantity relationship has not been validated in the EU-ETS. For instance, the 2018 price surge greatly anticipated the MSR's action. Prices also recovered quickly after the Covid-19 outbreak and stayed relatively high during the

[5] See Hintermann, Peterson, and Rickels, 2016 for an exhaustive review of the litterature on price drivers in the EU-ETS.

lock-down, which could not be due to action by the MSR, since it has a two-year delay. These elements raise the limits of the founding fathers models of emissions trading in predicting EUA prices. The framework of Montgomery, 1972 and Rubin, 1996 assumes, indeed, that the price path is determined by two market fundamentals: plants' marginal abatement costs, and the long term resource scarcity. However, the EU-ETS experience only partly validates these theoretical results. Importantly, the approach of Montgomery and Rubin does not take into account those price drivers that reside in changes in the inner market structure of the EU-ETS, and in market fundamentals, which we explore in this dissertation.

Static market structure

In the seminal model of static emission trading (Montgomery, 1972), carbon markets are analyzed with a single-actor. This approach abstracts from the mechanics of trading also referred to as the micro-structure of markets[6] (O'hara, 1997), including how they affect the price formation process. Yet, barriers to trading – usually grouped under the term of transaction costs – can drive a wedge between theoretical and practical market outcomes. According to the Coase theorem indeed, the permit market equilibrium will be independent of how the permits are initially distributed among regulated plants conditional on (i) property rights to pollute being clearly established and (ii) transaction costs being negligible. In presence of transaction costs in turn, the collective optimum cannot be safely decentralized and the mechanism will not be economically efficient.

In practice, indeed, frictions of various types are acknowledged to be pervasive as the empirical literature on permit markets attests (e.g. Carlson et al., 2000; Gangadharan, 2000; Hahn and Stavins, 2011; Jaraitė-Kažukauskė and Kažukauskas, 2015; Venmans, 2016; Karpf, Mandel, and Battiston, 2018; Naegele, 2018; Cludius and Betz, 2020) Yet, surprisingly, the prevalence of transaction costs and their implications for market outcomes as well as for policy design, evaluation and implementation are largely ignored in the theoretical literature on permit markets, with only a few exceptions (Stavins, 1995; Montero, 1998; Singh and Weninger, 2017). Chapter 2 fills this gap by tackling the issue of transaction costs in the EU-ETS: how do they materialize in permit trading, what is their impact on price formation and what are their implications for the design of supply-side policies?

Our analysis is motivated by stylized facts about firms' trading habits. Using transaction and compliance data from the European Union Transaction Log (EUTL) over Phase II (2008-2012), we find signs of autarkic compliance and impaired trading. At the extensive

[6]Defined by O'Hara as «the study of the process and outcomes of exchanging assets under explicit trading rules»

margin, about a third of firms (mostly small ones) did not trade at all on a yearly basis. At the intensive margin, active firms traded infrequently (typically a few times a year) and only for sufficiently high volumes, suggesting that marginal abatement costs are not equalized across firms in equilibrium. These results suggest that both fixed and variable trading costs[7] prevailed in the EU-ETS. In practice, fixed costs can correspond to exchange membership fees, plus other resources invested in operating a trading desk, monitoring the market and defining a trading strategy. Alternatively, variable costs can comprise search, information, brokerage, intermediation and consultancy costs.

Second, we relax Coases' assumption of negligible transaction costs and incorporate fixed and variable costs in the seminal model of permit trading. The fixed cost impacts firms' decisions to take part in the market (extensive margin) while the proportional cost further affects firms' trading choices by driving a wedge between their marginal abatement costs (intensive margin). In our framework, the permit price and firms' participation in and extent of trading are determined endogenously, and they depend on the given trading costs and firms' characteristics (i.e. abatement costs and permit allocations, where we let some firms be initially overallocated). This allows us to analyze the sensitivity of the market equilibrium to changes in the trading costs and firms' initial allocations.

Next, we analyze how trading costs could have influenced market price formation in the context of the EU-ETS, by calibrating the model's parameters to firms' individual characteristics. We first find that fixed and proportional trading costs in the order of 5-20 k€ per annum and 0.5-1.5 € per permit traded (or 3-11% of the permit price) are necessary to replicate observed EUA prices. Relative to zero trading costs, these costs reduce the discrepancies between firms' market participation and net market positions in the model vs. the data by 40%, and can rationalize 70% of autarkic compliance cases. Then, we appraise the implication of trading costs for supply-side policy design. In presence of a supply tightening, we find that trading costs have a positive effect on market prices, and result in additional compliance costs in the order of 7% relative to the frictionless scenario, due to foregone efficiency gains. Interestingly, our results also reveal that the distribution of allowance among firms have a notable influence on the extra compliance costs. Recall indeed that Coase's theorem (i.e. independence initial allocation) no longer holds in the presence of trading costs.

Messages can be drawn from Chapter 2 for future reforms of the EU-ETS. First, we learn that firms take little advantage of the first source of flexibility offered by the emissions trading scheme, i.e. spatial permit trading, due to trading costs in particular. The EU-ETS

[7] Those transaction costs related to permit exchanges.

is often perceived as a system of pollution licenses to autarkic firms indeed, which results in missing gains from trades. Thus, abatement efforts highly depend on the size of the permit endowment and the allocation method, which is an important source of heterogeneity between economic sectors.[8] Moreover, we learn from our results that supply-tightening policies tend to exacerbate differences in compliance costs, depending on the permit endowment. Consequently, a better effort sharing through the harmonization of the allocation method across sectors (such as the transition to full auctioning) would be beneficial in terms of cost efficiency. Moreover, support and transparency measures could be provided to alleviate trading costs, and help small firms access the market. A training offer to help regulated plants use the market place (the EEX) or set up a permit management strategy could be beneficial indeed, in terms of efficiency and avoided consultancy costs. A monetary compensation for brokerage fees[9] could also be envisaged for small emitters who are willing to enter the market.

Dynamic market structure

In chapter 2, we learned that transaction costs can impair the equi-marginal value principle outlined by Montgomery, 1972, leading to efficiency losses in the EU-ETS. Hence, the static market structure is determinant in market price formation. Recall however that carbon prices are also determined by a second, dynamic dimension which relies on the long-term scarcity of the pollution resource. As Rubin, 1996 showed, the price level primarily depends on the aggregate resource constraint indeed, namely the difference between $laisserfaire$ emissions and the emissions ceiling legally set by the regulator. In the seminal framework, the pollution level that would have prevailed in the absence of a regulation (or baseline emissions) is constant over time. This implies that the initial price level is entirely in the hands of the regulator, who decides on the resource constraint, i.e. the legal ceiling. However, it is unlikely to validate this assumption in practice. Like studies about the 2009 EUA price slump showed, baseline emissions are dependent on a variety of unobserved variables indeed[10] (De Perthuis and Trotignon, 2014). In fact, the MSR was implemented to absorb external pressures on market fundamentals, yet little attention has been paid to internal influences.

Chapter 3 seeks to remedy this gap, by considering the effect of technological progress on price formation. Technological progress is usually considered as induced by the pollution constraint indeed, which was very loose in the EU-ETS until the third trading

[8]For instance, the power sector, which receives all its allowances through auctions, is responsible for more than 25% of total realized emission reduction

[9]3,88€/1000tCO_2 at the EEX

[10]including exogenous variations in the production of goods, the use of international credits or overlapping environmental policies

period due to the permit over-supply. However, empirical studies evidenced an impact on low-carbon innovation and technological adoption by regulated plants (e.g. Borghesi et al., 2015; Calel and Dechezleprêtre, 2016; Calel, 2020). In turn, chapter 3 started from the intuition that technological change also has a feedback effect on EUA prices through market fundamentals of emission trading schemes: marginal abatement cost (m.a.c.) curves. By contrast to past empirical studies, we do not make any supposition regarding the type of technological change experienced by regulated plants, but let the data reveal it. Technological change can then be carbon-intensity decreasing or increasing, which we defined as directed (specifically, *strongly directed* when it is accompanied by a decrease in baseline emissions, and *weakly directed* when baseline emissions increase) and non-directed, respectively.

To elucidate the nature of technological change experienced by regulated plants over the period of interest, we develop a theoretical framework based on technological frontiers (Shephard, 1970; Chambers, Chung, and Färe, 1998). Using financial, micro-economic data from the EUTL[11] and the Amadeus[12] database, we then calibrate the yearly technological frontiers of seven manufacturing industries covered under the EU-ETS from 2013 to 2020. Our calibration approach is based on directional distance functions (d.d.f.). The preliminary analysis of industries' technical efficiency and technological change reveals that on average, high-carbon intensity plants experience more productivity gains than low-carbon intensity ones. Moreover, most plants carried out baseline-increasing technological progress on average, whether directed or non-directed, which puts perspective on the 'induced technological change' literature. Interestingly, directed technological progress tends to be baseline-decreasing (*strongly directed*) in industries with a high carbon intensity in 2013, like in paper or baked-clay manufacturing industries.

Next, calibrated technological frontiers enable us to compute industries' m.a.c. curves, using a revenue-maximization program, and to identify the effect technological progress depending on its nature. In our framework, m.a.c. are defined as the financial trade-off between production and pollution at the margin. Our analysis reveals that technological progress mainly impacts industry m.a.c. curves through its effect on baseline emissions. In particular, low carbon-intensity industries experience a substantial increase in their baseline emissions due to non-directed technological progress, which has a deflating effect on m.a.c. By contrast, emissions baseline of high-carbon intensity sectors generally decline under the influence of *strongly directed* technological change, which results in inflating m.a.c.

[11]European Union Transaction Log
[12]Bureau Van Dijk

Finally, using permit allocation data from the EUTL and computed m.a.c. curves, we compute permit demand and offer in our samples and solve the market equilibrium. Interestingly, we find that baseline-inflating technological progress is dominant and leads to increase the market clearing price above its observed levels, by 1.9 in 2013 to 38€/tCO_2 in 2020. Computing the net permit demand, we also observe significant permit transfers from low to high carbon-intensity industries. Yet, *strongly directed* technological progress alleviates the financial burden of permit purchases in high carbon-intensity industries.

Therefore, we learn from chapter 3 that technological progress can internally alter the market structure over-time, by inflating or deflating baseline emissions. This has, in turn, consequences on the market price, since the emission ceiling does not adjust to unobserved changes in permit demand. For instance, permit demand tends to decrease (increase) in the presence of directed (non-directed) technological change. As a policy implication, we raise the limits of the current allocation method in the EU-ETS, which relies on historical emission factors and product benchmarks calculated ten years ago. A grandfathering allocation method underrates the effect of technological progress on the effective abatement demand indeed, with impacts on market outcomes.

Carbon price floor: a remedy market to instabilities?

In Chapter 2 and 3, we learn that the market structure and market fundamentals are not fixed in the EU-ETS, which may lead to efficiency losses in both static and dynamic dimensions. For instance, at least three assumption of the founding models of emission trading are limited in practice: (i) constant market size (i.e. number of market participants) and optimal trading decisions by firms, (ii) constant marginal abatement costs and relatedly, (iii) predictable resource scarcity in the long run. These insights can elucidate, to some extent, the observed price volatility on the EU-ETS, and the limits of the Hotelling rule. They also raise the difficulty for market actors to form expectations about future prices, in the absence of predictable market fundamentals.

In this context, incorporating a price support mechanism in the EU-ETS has been identified as a potential remedy. In 2018, French president Macron proposed to lead the way with a German-French coalition at a level of 25-30€/tCO_2, and discussions have gained a renewed interest in face of the covid-19 oil-shock. Turning the EU-ETS into a so-called «hybrid» scheme could yield many benefits indeed. On the policy side, it would strengthen and affirm EU's commitment to reach its ambitious climate-neutrality target and lock-in revenues from auctions (Boehringer and Fischer, 2018). Besides, it could prevent myopic price formation by explicitly signalling the target cost of carbon, and bring more confidence to investors of the low-carbon economy (Edenhofer et al., 2017).

The last chapter of this dissertation contributes to the debate and the hybrid scheme literature, initiated by Roberts and Spence, 1976, by questioning the performance of a price floor in the EU-ETS under certainty and uncertainty. Specifically, we examine whether the support and stability functions of the Market Stability Reserve (MSR) in its current design, would be outperformed by a price-support policy. We focus on three plausible policies which secure the same minimum allowance price of 30€/tCO_2: an auction reserve price, a UK-style carbon price support (CPS) and a tax on emissions. We use a numerical model of emissions trading that is calibrated with market data from the EU-ETS power sector and includes the MSR as defined by the official EU directive, accounting for Phase IV revisions. By contrast to previous studies, we also account for investment decisions in the power-generation capacity, which can be fossil or renewable-based. We believe indeed they are particularly relevant in electricity production for their important «lock-in» effect.[13]

Our analysis reveals that policies which alter the permit supply to achieve a minimum carbon price, like the MSR and an auction reserve price, deliver better performances in their support function. By contrast, an extra fee on emissions or a carbon price only shift emissions in time, which may jeopardize the long term environmental integrity of the EU-ETS, especially as the initial permit surplus is large. We also find that supply-side policies are superior to stabilize EUA prices when future electricity demand is uncertain, since a small bank leaves less room for inter-temporal arbitrages. Last, we learn from the stochastic simulations that investment in a cleaner production capacity strongly correlate with the effective price of pollution faced by the power producer. As a result, the tax and the CPS reserve do not manage to maintain green investment when demand is unexpectedly low, nor do they provide a strong incentive to dismantle fossil capacity.

In summary, our analysis reveals that the MSR is not outperformed by any of the price support mechanisms, as it removes a large amount of allowances from the market and cancels them partly. According to our simulations, the permit bank is almost depleted under the action of the MSR indeed. An auction reserve price slightly improve emission reductions, but at risk of uncontrollable marginal abatement costs in case of a positive demand shock. In turn, the MSR may be preferred to an auction reserve price as it provides a «safety valve» if the permit scarcity becomes too high. In the broader framework of this dissertation, two messages can be drawn to reform the EU-ETS. First, the MSR's support function seems to perform well, in that it restores the permit scarcity due to

[13] The life expectancy of power plants usually ranges from 20 to 60 years

short-run permit cancellations. Therefore, we argue that the cancellation mechanism plays an important role, especially in the current context of coal phase outs. Second, the MSR's stability function is more ambiguous. Due to delays in its action and its lack of predictability, it may add another layer of uncertainty to an already unstable market structure. From this point of view, turning quantity into price bounds may be an alley to explore.

Chapter 1

EU-ETS crises and reforms: a matter of supply and demand ?

1.1 Introduction

In 2005, the European Union decided to equip itself with a market-based instrument aimed at controlling CO_2 emissions at the levels imposed by the Kyoto protocol, later taken over by the Paris Agreement, in order to prevent global temperatures rise by more than 2°C above pre-industrial levels before the end of the century. First hailed as the successful implementation of a large scale, sophisticated instrument, the European union Emissions Trading Scheme (EU-ETS) proved that a market for pollution rights can work in practice, and that the European cooperation could achieve impactful actions in order to tackle major challenges. Yet, the instrument soon ran into difficulties.

Actually, the main controversy stemmed from the mere definition of the EU-ETS' goals. According to what we can refer to as an 'economists view', the EU-ETS was nothing else but a price discovery tool designed to reach a quantitative emissions target, which it has always achieved in the past. By contrast, policy makers tended to put forward the implicit goals of the EU-ETS, namely to drive the low carbon transition, including in other sectors of the EU's economy, and put forward the pioneering role of the EU in climate action. As such, prices delivered in the second trading period (2008-2012) were perceived 'too low', by comparison to other target costs of carbon adopted in EU's member states, such as carbon taxes or tutelary values of CO_2. In turn, the EU-ETS has undergone multiple reforms since its third Phase (2013-2020) with two objectives: raising short term permit (or European Union Allowance) prices, and stabilize their trajectory.

This first chapter provides a critical overview of crises, reforms and challenges experienced by the EU-ETS, since its implementation to this day. In particular, we point out that supply-adjusting reforms have been designed under the assumption of a valid, instantaneous price/quantity relationship, which has long been questioned by scholars and disregards the micro-economic market structure of the EU-ETS. This strategy seems to have succeeded in raising short-term EUA prices, although the price volatility issue left unresolved. Yet, the EU-ETS is bound to new challenges and reforms in the upcoming Phase 4 (2021-2030), in a context of increased environmental ambition set by the European Green Deal, an acceleration of unilateral climate policies and the current economic crisis. Thus, will the EU-ETS avoid history repeat itself, and be up to the task ?

This chapter adopts a historical approach. Section 1.2 goes back to the creation of the EU-ETS and outlines its basic principles, Section 1.3 reviews Phase 2's price slump and the subsequent loss of confidence in the market, Section 1.4 describes supply-adjusting reforms undergone at the beginning of Phase 3, and Section 1.5 outlines some future challenges to be faced by the EU-ETS in Phase 4.

1.2 A chief instrument for EU's climate policy

1.2.1 Legislative context

As Ellerman, Marcantonini, and Zaklan, 2016a point out, the European Union Emissions Trading Scheme (EU-ETS) was informally born in 2000 when the European Commission published its *Green Paper on Greenhouse Gas Emissions Trading*[1]. The paper was intended to launch a discussion about implementing a cap-and-trade scheme within the European Union, in order to meet the greenhouse gas emissions reductions the EU had committed itself to achieve under the Kyoto Protocol. The legally-binding treaty, ratified in 1997 under the united Nations Framework Convention on Climate Change (UNFCCC), urged major emitters to reduce their emissions by an average of 8% below 1990 levels in the first commitment period (2008-2012), and by 20% in the second commitment period (2013-2020).

Therefore, a cap-and-trade mechanism established itself as (i) a means of securing the environmental commitments of EU member states vis-à-vis the Kyoto Protocol, and (ii) a lever for the Commission to affirm its leading role in climate change policy (Convery, 2009). The design of the EU-ETS being laid out in the green paper, a 3-year «learning-by-doing» pilot was set up in 2005 in order to prepare for the second trading phase, which would coincide with the first Kyoto commitment period. The ETS Directive 2003/87/EC was adopted in 2003 and the EU-ETS was officially launched in January 2005. Originally, the mechanism was highly decentralized and relied on the development of National Action Plans (NAP). In particular, each country proposed their own national cap and the distribution of allowances among regulated installations. However, this bottom-up

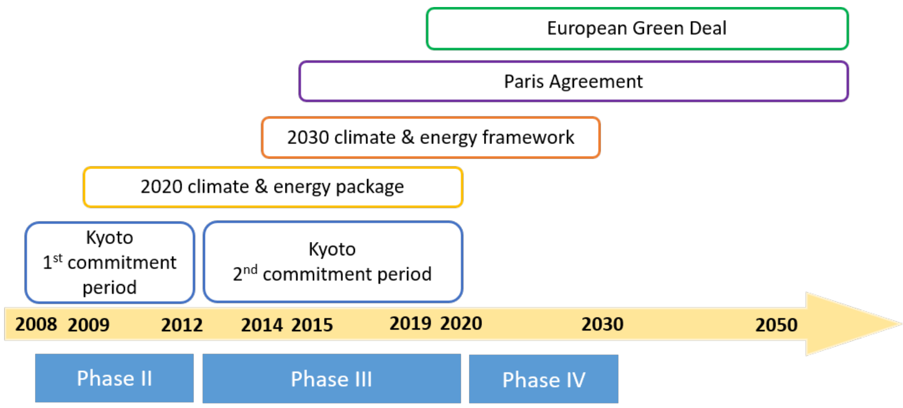
[1] https://op.europa.eu/en/publication-detail/-/publication/41ab9f93-b438-41a6-b330-bb0491f6f2fd/language-en

system rapidly proved to be cumbersome and was reformed in Phase 3 to adopt a single, EU-wide cap centrally set.

The Kyoto framework was taken over by the Paris Agreement, after UNFCCC negotiations in the 21st Conference of Parties (COP) on measures to be taken after the second commitment period ends in 2020. Adopted in 2015, the Paris Agreement has set the qualitative goal to limit global warming to well below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C. To achieve these targets, countries would have to come up with nationally determined contributions (NDCs) explaining their climate action plans. Countries would then have to participate to a quinquennial global stocktake to assess emissions abatement efforts and report their low-carbon strategy.

In order to secure the alignment between its short-term climate policy and longer-term targets, the EU has equipped itself with emission reductions milestones up to 2050. First, the 2020 climate & energy package is a set of binding legislations enacted in 2009. It sets EU's «20-20-20» target, namely a 20% decrease in emissions relative to 1990 levels, 20% of renewable energy in the electricity mix and a 20% improvement in energy efficiency. Next, the 2030 climate & energy framework set updated targets of 40% emission reductions in 2030, a 32% share of renewable energy and a 32.5% improvement in energy efficiency. The framework was adopted in 2014.

FIGURE 1.1: Timeline of EU's climate legislation and EU-ETS trading periods



The European Parliamentary elections in May 2019 revealed an increased concern for environmental issues, with a larger-than-ever green leaning MEPs. In particular, the European Council largely endorsed the carbon neutrality target, materialized in the European Green Deal (EGD) presented in 2019 by Ursula von der Leyen. With the EGD, the European Commission clearly affirmed the ambition of making EU's economy carbon neutral by 2050, and proposed to increase the 2030 emissions reduction target to 50% compared to 1990 levels. In particular, a «European Climate Law» has been handed out in March 2020, with the purpose of writing targets set by the deal into law. The EGD changes the regulatory framework of EU's climate policy and, accordingly, amendments to the 2030 climate & energy framework and ETS Directive will be proposed in 2021 (Marcu et al., 2020).

At the European level, the EU-ETS has been a key tool to enforce the Paris Agreement. In the case of France, the EU-ETS plays an important role in the achievement of the *Stratégie Nationale Bas Carbone* (SNBC), the national roadmap for a climate neutral economy in horizon 2050. The SNBC, published in 2015, inherited from the *Loi de transition Energétique pour la Croissance Verte*, and relies on the definition of carbon budgets in all sectors of the economy. Greenhouse gas reductions are more ambitious than the EU's in the industrial sector, since France aims for a 35% abatement in 2030, relative to 2015 levels[2]. The carbon-neutrality goal was written in the French law recently, as part of the *Loi Energie Climat* enacted in November 2019.

1.2.2 Governance

Like any other propositions of the European Commission going through the ordinary legislative procedure, amendments to the EU-ETS Directive have to be voted by the European parliament and Council after two alternate readings. The procedure used for voting in the European conciliation committee (equal no. of Parliament and Council members trying to agree on joint text) is the qualified majority system, which enables the EU to take decisions without the need for unanimity, yet going beyond a simple majority of voters. More precisely, a proposition is adopted if (i) 55% of member states (14 out of 27 without the UK) give their agreement, and (ii) these states represent at least 65% of EU's population.

Given the great heterogeneity in member states' economies and emission needs, the EU-ETS has been difficult to reform in the past as interests diverge. Figure 1.3b shows the geographical distribution of emissions in EU-28 (noting that the UK will soon leave the system) over the third trading period (2013-2019). It reveals that Germany, Poland, the UK and Italy are the biggest emitters. Although absolute emissions do not tell about countries' carbon intensity, these countries are known to have a relatively carbon-intensive energy mix, by contrast to France or the Nordic countries, which are more reliant on nuclear power and renewable energy sources, respectively. In Germany for instance nearly 20% of electricity is produced from brown and hard-coal in 2020[3].

[2] https://www.ecologique-solidaire.gouv.fr/
[3] https://www.energy-charts.de/energy_pie.htm

Consequently, member states are not equal in face of an increase in climate ambition, and in the carbon price. For instance, France who is a net electricity exporter could benefit from an increase in electricity prices due to the tightening of the EU-ETS' emissions ceiling. By contrast, eastern countries would suffer from an increase in both their import costs and dearer production costs, with repercussions on the domestic electricity price. Negotiations to reform the EU-ETS are often long-lasting and strong-armed in turn. For instance, it took two years and a half for an agreement to be reached between the European parliament and council about Phase IV reform, which included measures to re-balance the market[4].

To support lower-income (and highly carbon-intensive) countries in their energy transition, measures have been taken. The modernisation fund is dedicated to help the 10 lower-income countries modernising their electricity system and improve energy efficiency. Besides, a derogation was granted for eastern Europe electricity producers to receive free allocation, even after 2013. Despite these measures, political tensions remain regarding the financial burden imposed to participating countries. Recently, polish officials expressed how they should «scrap the emissions trading scheme» to focus on fighting the coronavirus.[5]

1.2.3 EU-ETS basic rules and coverage

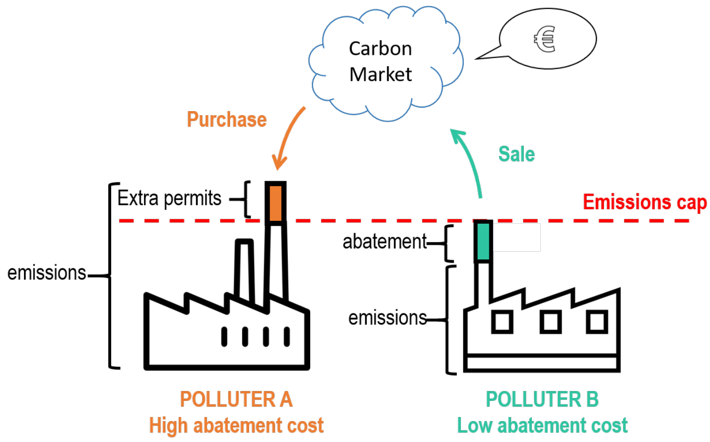
The EU-ETS (from Phase 2 on-wards) is the largest carbon market worldwide, and covers about 45% of greenhouse-gas emissions in 31 countries of the European Community, namely the 28 member states plus Iceland, the Liechtenstein and Norway). It includes every industrial plant or power station with a net heat excess of 20 megawatt across many sectors, except for aviation, which joined the system in 2012. More precisely, only flights from and within the EU are concerned by the EU-ETS, in the absence of a global agreement.[6] As Figure 1.3a shows, electricity production is by far the highest permit-consuming sector, followed by cement and metallurgy. Besides carbon dioxide (CO_2) generated by power and heat generation, as well as commercial aviation, installations must report any nitrous oxide (NO_x) from chemical compounds manufacturing and perfluorocarbons (PFCs) from aluminum production.

[4]https://www.politico.eu/wp-content/uploads/2017/11/Grand-compromise-on-ETS-reform-set-to-tighten-market-copy-2.pdf, Thomson Reuters, 2017

[5]https://www.euractiv.com/section/emissions-trading-scheme/news/eu-should-scrap-emissions-trading-scheme-polish-official-says/, 2020

[6]International flights are yet subject to the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), an emission mitigation approach for the global airline industry

FIGURE 1.2: Carbon market operation



As any cap-and-trade system, the EU-ETS is a quantity regulation which sets an annual, global cap on emissions ceiling (2,084 billion tCO_2 in 2013) disseminated among polluting plants, by means of free allocation or auctions. When freely allocated, allowances are directly donated to the installation based on a grandfathering calculation method. Alternatively, two allowance platforms deliver European Union Allowances (EUA): the European Energy Exchange (EEX) in Leipzig, and the InterContinental Exhange (ICE) in London, which acts as UK's plateform. After 2020 however, the EEX will take over the ICE as a single market place due to Brexit. Auctions are usually organized bi-weekly and follow a single round, sealed bid, uniform price format.[7]

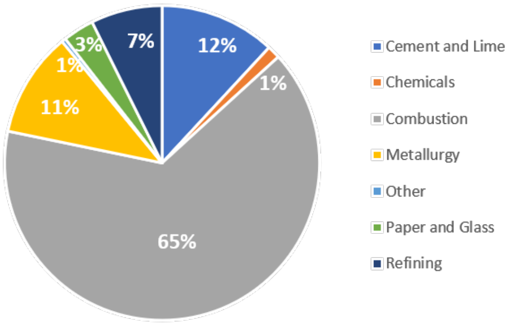
Once privately owned, allowances can be traded in the secondary market, by installations or accredited account holders like financial intermediaries. In principle, trading allows high marginal abatement cost plants to buy pollution permits from low marginal abatement costs in a win-win exchange (Figure 1.2). Allowances can be traded over-the-counter or through an organised market. Moreover, the EEX proposes three emissions products : a spot contract continuously traded, futures contracts (with monthly, quarterly and yearly expiries) and an option contract on December futures[8]. Since 2008, traded volumes have increased continuously, and reached about 9.8 billion allowances in the secondary market in 2018[9]. They include 74% of futures contracts and a minority of spot and over-the-counter trades, indicating the omnipresence of financial actors.

Besides being financial assets, the primary function of allowances is to cover emissions for compliance with the EU-ETS. Installations must report their verified emissions for the previous calendar year no later than March (Figure 1.4), and surrender as many allowances to the regulatory authority by the end of April. If any, extra allowances

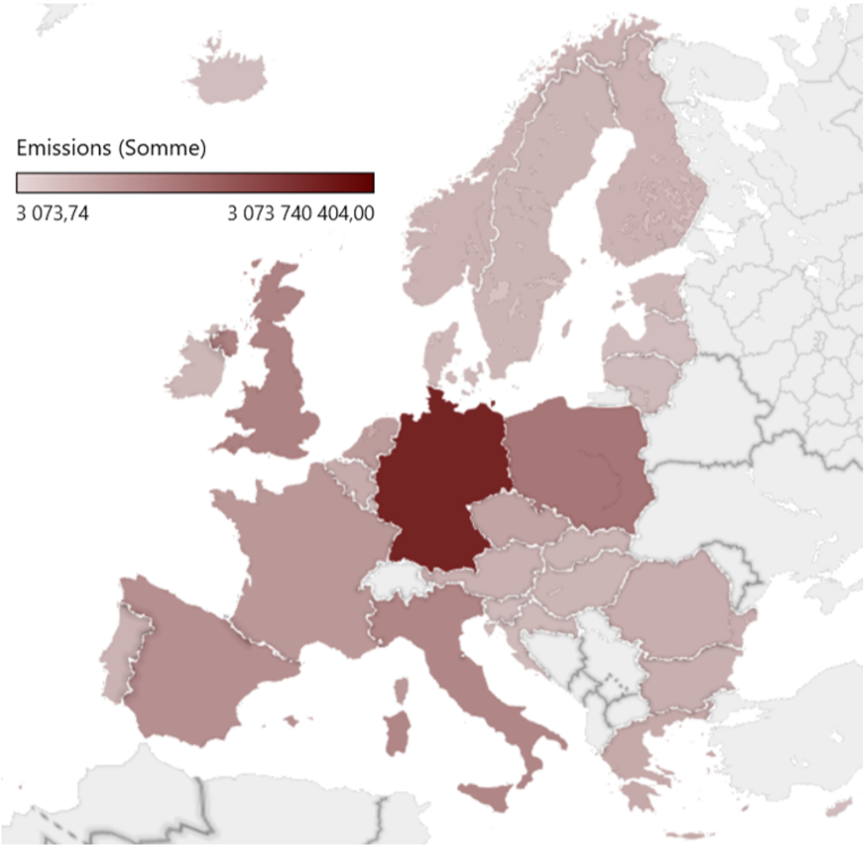
[7] https://www.eex.com/en/markets/environmental-markets/emissions-auctions
[8] EUAs come in lots 500 (1000) in the primary (secondary) market
[9] https://ec.europa.eu/clima/sites/clima/files/ets/auctioning/docs/ger_report_2018_en.pdf

FIGURE 1.3: Distribution of allowances by sector and country

(A) 2008 data, source EUTL



(B) Total emissions over 2013-19, source: EEA, plot: author



can be stored for future use on installations' electronic accounts: this is the well-known *banking* provision, enabling inter-temporal arbitrages. Cost-minimizing and rationally behaving plants would indeed carry out extra abatement efforts in the early days of the scheme, and use banked permits to alleviate higher future compliance costs (Rubin, 1996)[10].

[10]hence the «bell-shaped» banking curve.

The *borrowing* of allowances is forbidden, namely plants cannot hold a negative amount of permits on their electronic accounts, or short-sell permits. Yet, the timing of compliance makes it possible to implicitly borrow allowances from the following year's allocation. Note indeed that permit allocation occurs in February while reconciliation takes place a few months later. According to Szabo, 2019 from Carbon Pulse, the forward-borrowing of allowances has become a common practice among polluters who needed to raise cash after the 2009 crisis. However, analysts warn that they might face a «rude awakening» when the time comes to close their position (allowances delivered in Phase 4 cannot be used for 2020 compliance), at a higher-than-ever carbon price.

Transparency of the emissions trading scheme and fraud prevention is ensured by the Monitoring, Reporting and Verification (MRV) system. The M and R parts, namely emissions accounting and data collection, are the polluter's responsibility, who must propose an emissions reporting methodology to the Competent Authority (CA) for approval. Emission reports are then verified every fall for the previous trading year, and the sanction for under-reporting amounts to 100€/tCO_2 since 2008. The traceability of allowance movements is ensured by the European Union Transaction Log (EUTL), which records EUA transactions and compliance status. Transactions are published on a public website[11] with a 1-year delay.[12] Besides, in reaction of the carbon VAT fraud of 2008-09, the Markets in Financial Instruments Directive (MiFID) was revised to cover the spot trading of allowances.[13]

1.3 Phase 2: the EU-ETS in crisis

1.3.1 Design features

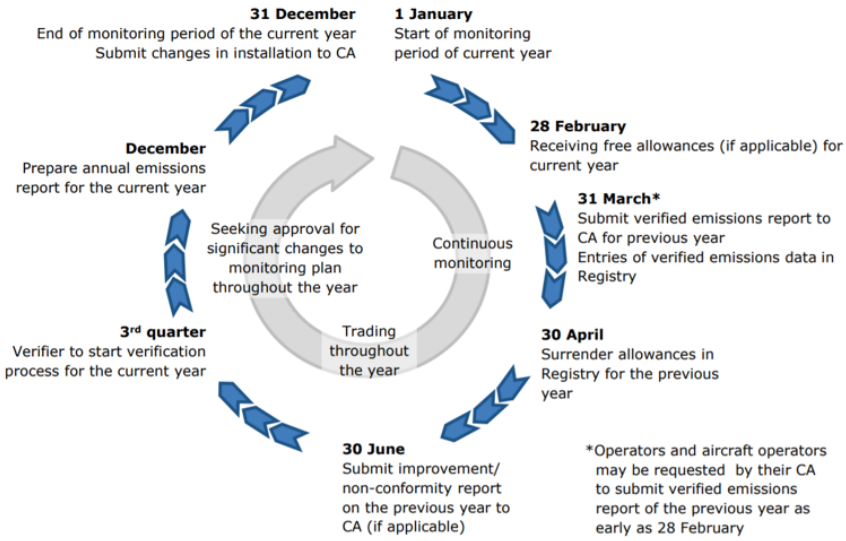
The second trading period inherited from the successful implementation of the pilot phase (2005-2007). Yet, and because of the lack of accurate data about emissions, permit endowments had largely been over-estimated during Phase 1, resulting in a price collapse in 2007. Consequently, 2008 was a fresh start, with new allowances and an emission ceiling reduced by 6.5% relative to 2005. In practice, the emission cap was determined as the sum of countries' own ceilings until 2013. In turn, the exact figure

[11] https://ec.europa.eu/clima/ets/

[12] EU-ETS handbook: https://ec.europa.eu/clima/sites/clima/files/docs/ets_handbook_en.pdf, p.78

[13] The carbon fraud was a carousel-type. A company A bought EUAs from a foreign European country exempt of VAT, then sold them domestically to a fictive society B all taxes included. Next, society B could sell it back internationally, and reclaim the VAT to the domestic country. Society A then disappeared before paying back the VAT it owes to the domestic state.

FIGURE 1.4: EU-ETS compliance cycle



Note: EU-ETS handbook, European Commission, p.102

is unknown, though like in Phase 1, most allowances were given out for free (approximately 90%, versus 10% auctioned).

Regulated plants were also allowed to use international credits for compliance, which could be earned from two mechanisms set up under the Kyoto protocol. First, the Clean Development Mechanism enabled Annex 1 countries to invest and demonstrate the success of low carbon projects in developing countries, and second, the Joint Implementation (JI) enabled industrialised countries to invest in projects that reduce emissions in other industrialised countries. CDM and JI projects generate Kyoto credits referred to as Certified Emissions Reductions (CER) and Emission Reduction Units (ERUs) equivalent to 1 ton of CO_2. The upper limit for international credit use was set at the discretion of National Action Plans, except for aviation where there was a 15% tolerance.

Finally, the EUTL (single transaction and emissions electronic registry) replaced national registries and the Community Independent Transaction Log. This greatly simplified the MRV process for both plants and the Competent Authority, as the EUTL automatically checks, records and authorises transactions between accounts and the union registry.[14]

1.3.2 The price is (not) right

During Phase 2, allowance trading quickly picked up and increased from an annual volume of 2.3 million EUAs in 2008 to 7.9 million in 2012.[15] Less than half of trades took place «over-the-counter», and the other half through a carbon exchange. The evolution

[14] https://ec.europa.eu/clima/policies/ets/registry_en
[15] EU-ETS handbook : https://ec.europa.eu/clima/sites/clima/files/docs/ets_handbook_en.pdf

of trading volumes can suggest a rapid learning of allowance trading from emitters and a relatively liquid market, which is usually the sign of a well-functioning market (less risk, enhanced price discovery). Liquidity plays an important role in carrying new information in asset prices indeed (Ibikunle and Gregoriou, 2018). However, these figures also reflects the growing interest of more-or-less benevolent financial actors in carbon trading. For instance, more than 80% of trades concerned derivative products (Patay and Alberola, 2012), not to mention the three incidents that took place in 2008 and 2009 (VAT fraud, phishing of quotas and the reselling of already reconciled permits by Hungary).

Notwithstanding the increasing trading volumes and a promising kick-off, prices rapidly declined from mid-2008 to the end of Phase 2, which attracted lively criticism. As Figure 1.5 shows indeed, the EUA price dropped in 2009, and followed a decreasing trend around 10-15€/tCO_2 thereafter. Although the EU-ETS functioned well from a strictly technical point of view (it delivered a carbon price and enabled permit trades), it had also been presented as a key driver of the EU's low carbon transition by European policy makers. Therefore, environmental advocates expected it to yield a carbon price that is «high-enough» to make renewable energy sources compete with fossil, and steer capital to low-carbon investments.

Although such a price is difficult to pinpoint, some elements led the climate community to believe that the EUA prices were to low to guarantee the environmental integrity of the EU-ETS. First, EUA prices were consistently below the coal-to-gas switch price in Europe (Zachmann, 2015) in Phase 2, jeopardizing the long-run retirement of coal and lignite power plants in eastern Europe. Second, EUA prices were often confronted to the target value of carbon resulting from cost-benefit analyses. For instance, the well-know global abatement cost curves of McKinsey, 2009 show that the complete cost of low carbon technologies like CCS or solar PV lie above 30€per tonne of CO_2 avoided. In France, the «tutelary» value of carbon presented in the Quinet report (Quinet, 2012), and recommended to guide public and private investments, had been evaluated at 90€/tCO_2 in 2020 and 250€/tCO_2 in 2030.[16] Although these carbon prices result from different evaluation methods, their high values dampened the credibility of the EU-ETS.

Furthermore, much doubt has been raised about the ability of the EU-ETS to implement the polluter-pays principle, an article[17] of major French NGO *Réseau Action Climat* points out. In principle, the price of carbon should indeed - conditional on the emissions cap

[16]This value is based on a cost-effectiveness analysis, to evaluate the minimum return on investment in low-carbon technologies necessary to attain the goals set by the *Stratégie Nationale Bas Carbone*.

[17]https://reseauactionclimat.org/thematiques/europe/

being perfectly calibrated - reflect the social value of the carbon externality, just like a Pigouvian tax. However, in many member states, carbon taxes turned out to be much higher than EUA prices at the time. In Sweden for instance, the carbon tax amounted to 96€/tCO_2, 55€/tCO_2 in Finland and 23€/tCO_2 in Denmark (Metivier et al., 2017). Besides, studies evaluating the Social Cost of Carbon, usually estimated as the net present value of the damages generated by one additional tonne of carbon emitted to the atmosphere today, found a range of 40-150€/tCO_2 in the UK (Watkiss and Downing, 2008), and 44US/tCO_2$ in the US (Nordhaus, 2011).

The third set of critiques focused on the generous free allocation of permits to installations over Phase 2, which could have generated important windfall profits for polluters – when plants are over-subsidized for their pollution (Aldy and Stavins, 2012). As WWF pointed out in a 2010 article: *«German power companies have made windfall profits that amount to €39 billion and several energy intensive German companies, such as steel producers ThyssenKrupp and Salzgitter, will profit from hundreds of millions Euros through the sale of surplus emission allowances»*. Moreover, and although the power sector gradually transitioned to an auctioning allocation method, some sectors like cement production or metallurgy notoriously received more allowances than needed[18], which jeopardized the credibility of the EU-ETS.

1.3.3 External reasons for the price drop

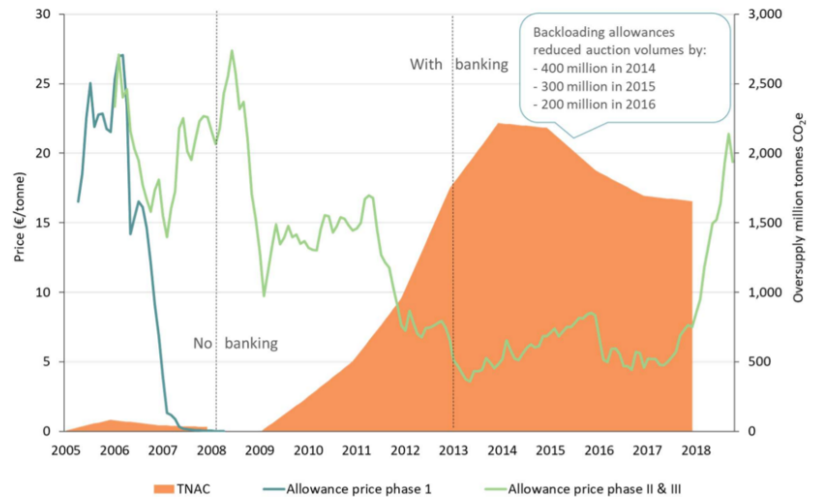
The 2009 price drop has been studied in numerous academic papers and policy reports, and was largely attributed to a supply-demand imbalance of permits. For instance, Figure 1.5 shows that the total number of allowance in circulation (TNAC), namely the difference between allowances allocated and surrendered, grew rapidly over the second trading period.[19] At the end of 2012, the permit surplus was nearly worth almost a year of emissions.

Three main factors have been held responsible for this accumulation. First, the deep and lasting economic crisis in Europe, which caused emissions to decline due to a production slow-down, mechanically reducing demand for allowances. Moreover, the expectation of a slow recovery proved to have a downward effect on the long term price trend (Koch et al., 2014; Aldy and Stavins, 2012). Yet, Gloaguen and Alberola, 2013 find in an econometric analysis that the economic recession only contributed up to 25% to the oversupply of permits. The presence of unilateral, overlapping environmental policies, also played a crucial role indeed. According to the authors, about 50% of the permit surplus

[18]for competitiveness reasons and lobbying, among other things (Earth Europe, 2010)
[19]EUAs were non-transferable from Phase 1 to Phase 2.

would be due to the generous support to renewable energy, and about 15% due to improvements in the energy-efficiency of production. For instance, low-carbon electricity production capacity grew by more than 35% between 2008 and 2012[20] as a result of the 2020 climate & energy package targets, which led to set up feed-in-tariffs for renewable energy sources. Third, Neuhoff et al., 2012 point out that the high use of international credits added up to the supply of allowances. During the second trading period, covered installations used 1.058 billion tonnes of CO_2 worth of CERs/ERUs indeed, which were transferred to Phase 3 if unused.[21]

FIGURE 1.5: EUA prices and bank



Notes: *The total number of allowances in circulation (TNAC) reflects the allowance surplus and is determined each year as the total allowances issued minus the allowances surrendered for compliance, taking into account international credits used for compliance and allowances already in the reserve (European Commission, 2015b).*

Source: *Vivid Economics*

The 2008-12 price slump created debates about the true objective of the EU-ETS. Two schools of thoughts, which can be referred to as the «economist» *versus* «policy maker» emerged in turn. On the one hand, economists have tended to see the EU-ETS as a mere price discovery instrument helping polluters to comply with GHG regulation. In this view, observing a certain amount of banking is normal; moreover, it materializes the willingness of polluters to optimize their abatement costs over the duration of the program (i.e. make inter-temporal arbitrages). The large permit surplus should not be alarming in turn, as long as the environmental target is respected. In the extreme, a carbon price going to zero would mean that the pollution problem is solved, as there is no demand for abatement.

On the other hand, policy makers have favored the unstated objectives of the EU-ETS, namely driving low-carbon investment in the long-run and promote the EU as a pioneer

[20] https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-2/assessment-4

[21] https://ec.europa.eu/clima/policies/ets/credits_fr

in climate action. In such a view, which abstracts from an economic efficiency logic, the price level is the main performance indicator of the EU-ETS. Consequently, the EU-ETS should be designed so as to deliver higher prices immediately. In turn, and taking into account the limited rationality of market actors, this view rather favors to cutback the permit supply in the short run, in a static supply/demand logic.

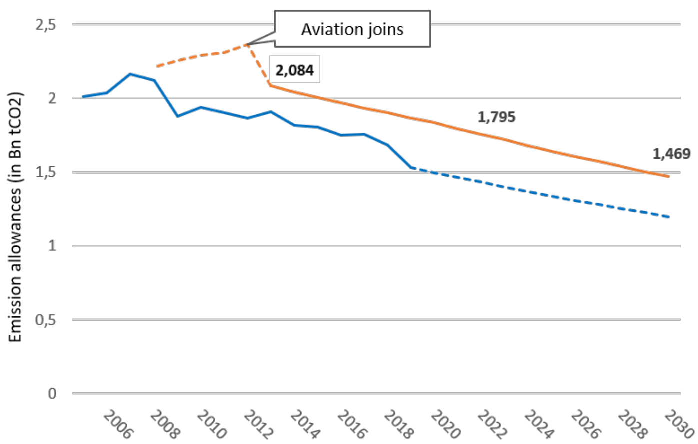
1.4 Phase 3 reform: cutting-back supply

Although opinions differed about the objective of the EU-ETS, there was a consensus that the supply imbalance was excessive in 2012. Moreover, criticism formulated about EUA price levels urged policy-makers to reform the EU-ETS before the third Phase (2013-2021), which coincided with the second Kyoto commitment period.

1.4.1 Design adjustments

Amendment to the EU-ETS directive published in June 2009 included several design changes. As of Phase 3, an EU-wide emissions ceiling replaced national NAPs, and was set at 2,084,301,856 allowances decreasing at a rate of 1.74% annually, the Linear Reduction Factor (LRF). The LRF was calibrated to reach the 2020 climate & energy package targets, namely a 20% emissions reduction by 2020 relative to 2005 levels. Figure 1.6 displays the cap trajectory from 2013 on-wards.

FIGURE 1.6: Target path and verified emissions



Note: Data source: EEA, European Commission. The emissions cap of Phase 2 is computed using allocation figures from EEA plus 10% (proportion of auctions).

Since 2013, auctioning is the default allocation method and the power sector must buy all of its allowances in the primary market.[22] Over the period, the share of permit auctioned is estimated to reach 57%. Yet, free allocation has been progressively replaced by auctions in the manufacturing industry, mainly for carbon leakage and competitiveness reasons. In turn, 80% of allowances was handed out for free in the manufacturing industry in 2013, down to 30% in 2020. By contrast to Phase 2, installations' free permit endowment is calculated based on reference values of carbon intensity or benchmarks. Benchmarks are defined as the average of the 10% most efficient installations in terms of CO_2 emitted per ton of product produced, and have been developed for 54 manufacturing products, based on the consultation of various stakeholders (see the sector specific guidance.[23]

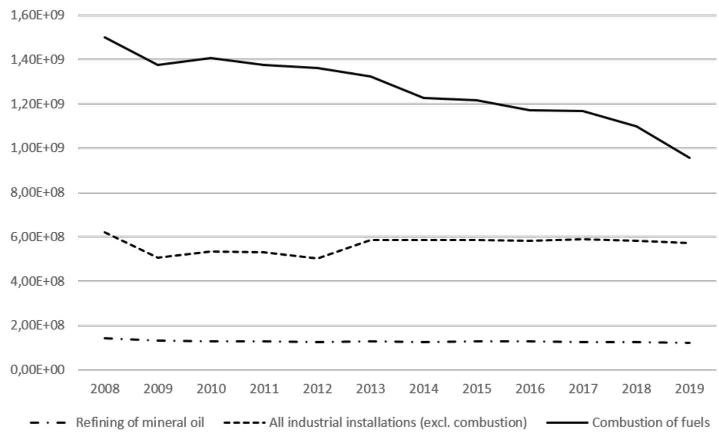
The allocation size is then computed as follows: a first estimate is obtained by multiplying the product benchmark by a historical activity level (HAL), which corresponds to the median annual production in the baseline period (2005-2008 or 2009-2010). The HAL can be updated in case of production and capacity adjustments. Next, two correction factors are applied to obtain the final allocation. First, a Carbon Leakage Exposure Factor (CLEF) is applied to prevent industries from relocating their production in countries outside the EU with less ambitious, or nonexistent carbon pricing policies. The CLEF is set at 1 for sectors at significant risk of carbon leakage, and 0.8 decreasing linearly to 0.3 in 2020 for the remaining sectors. Second, a cross-sectoral correction factor (CSCF) is applied to ensure that total allocation does not excess the annual emissions ceiling.[24] The final allocation is then computed as

$$A_i = BM_i \times HAL_i \times CLEF_i \times CSCF_i$$

Therefore, the mechanism rewards the cleanest producers, who receive all the allowances they need to cover production, and incentivizes more carbon-intensive installations to carry out abatement measures or buy allowances to cover their emissions. For the time being, the only empirical evaluation of benchmarks is a study by Sartor, Pallière, and Lecourt, 2014, who show that the new allocation rules reduce the scope for windfall profits in energy-intensive industries while also effectively mitigating carbon leakage risks. Yet, Marcu et al., 2020 find that the carbon intensity of the manufacturing industry has remained relatively stable since 2013, calling for further impact evaluations of the performance of benchmarks. Figure 1.7 shows indeed that most emission reductions are done by the combustion sector, while industrial emissions have increased over-time.

[22]Except for some less-wealthy member states who benefit from a derogation
[23]https://ec.europa.eu/clima/sites/clima/files/ets/allowances/docs/p4_gd9_sector_specific_guidance_en.pdf
[24]Guidance avalaible at https://www.emissions-euets.com/cross-sectoral-correction-factor-cscf

FIGURE 1.7: Emissions by sector, source EEA



1.4.2 Supply-adjusting measures

Backloading. In order to manage the large permit surplus accumulated over the second trading period, a decision was made to postpone the auctioning of 900 million allowances, by amending the EU-ETS auctioning rules. The «back-loading» procedure froze 400 million allowances in 2014, 300 million in 2015 and 200 million in 2016. Although it coincided with a price recovery (figure 1.5) and helped reducing at least part of the permit surplus, the back-loading measure has often been qualified as a short term fix, that suffered from two main flaws.

First, back-loaded allowances were not cancelled, meaning that the measure left the environmental ambition of the EU-ETS unchanged. Economists expect the procedure to have little impact on EUA prices indeed, with rational agents optimizing dynamically and without informational constraint. However, the sole political announcement proved to influence EUA price formation, Koch et al., 2016 show, but not in the expected direction. In the absence of a firm commitment to make cap-adjusting reforms, the authors find that back-loading failed to anchor higher price expectations. This is particularly true as market actors include, for a large part, well-informed and responsive financial actors. Second, the back-loading of allowances does not solve the supply-side rigidity of the EU-ETS, and its ability to absorb future economic shocks. Thus, it may have further dampened the time-consistency of the mechanism (Marcu, 2012). To tackle this issues, Perthuis and Trotignon, 2014 called upon the implementation of an independent carbon governance which would act like a carbon central-bank.

Market Stability Reserve. To address these long-run weaknesses, the European Commission decided to bring a structural change to the market design by proposing a Market Stability Reserve (MSR) in its communication titled «A policy framework for climate and energy in the period from 2020 to 2030». The MSR behaves like a quasi-automatic stabilizer that aims at controlling the volume of allowances in circulation. In the European Commission's words, the goal of the MSR is twofold: (i) address the current surplus of allowances and (ii) improve the system's resilience to major shocks by adjusting the supply of allowances to be auctioned.

Presented in 2014 and adopted in 2015 by the European Parliament, by amendment of the EU-ETS Directive, the MSR was scheduled to start operating in 2019. It operates on the basis of the allowance volume in circulation or TNAC computed as

$$TNAC = \text{Supply} - (\text{Demand (including cancelled allowances) + allowances in the MSR})$$

The MSR was initially seeded with the 900 million EUA backloaded, plus unallocated allowances from the New Entrants Reserve and due to production or capacity changes.[25,26] In its initial design, the MSR was tuned to remove 12% of the following year's auction when the TNAC exceeded 833 million allowances, and inject back allowances in the market when it fell under 400 million allowances, at a rate of 100 million EUA annually.

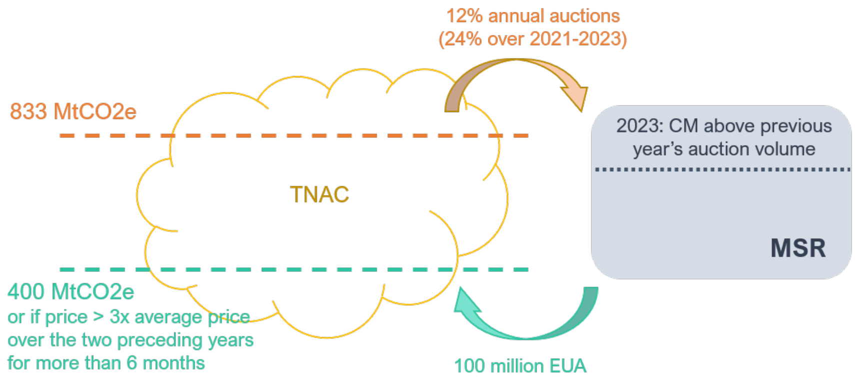
However, in the context of Phase 4 revision and the strenghtening of climate targets in line with the 2030 climate & energy package, the intake rate was temporarily strengthened to 24% from 2019 to 2023, with the regular 12% rate restored from 2024 onward. Moreover, the MSR was equipped with a cancellation mechanism scheduled to start operating in 2023 in order to increase the ambition of the EU-ETS. In turn, it became «cap-adjusting» in that the emissions ceiling depends on the banking of allowances. The cancellation mechanism permanently removes allowances held by the MSR above the previous year's auction volume. Figure 1.8 summarizes MSR rules in June 2020.

Expected impacts. As figure 1.6 shows, verified emissions have always lied below the ceiling, questioning the need of supply-adjusting measures at all. This confirms that the MSR was mainly designed to achieve the unstated objectives of the EU-ETS, namely raising the near-term price of allowances to endorse EU's climate ambition, beyond a price discovery objective. In this view, the backloading of permits and the MSR seem to be successful so far. Their implementation have indeed been accompanied with an unprecedented price hike above 30€/tCO_2 in July 2019, with the EUA price regularly exceeding 25€/tCO_2 since then. Moreover, forecasts estimate prices to exceed 40€/tCO_2 in 2030 (Schjolset, 2014; Mauer, Okullo, and Pahle, 2019).

[25] The New Entrants Reserve (NER) is a pool of pollution permits set aside for new installations, which are eligible for free allocations in phase 3.

[26] https://www.vivideconomics.com/casestudy/interactions-between-market-stability-measures-in-linked-carbon-markets/

FIGURE 1.8: MSR rules in June 2020



To this day, the exact amount of allowances removed from auction by the MSR is unknown (it should be published in 2020), but estimates range from 550 to 700 million allowances.[27] However, economists agree that allowance cancellations could be significant by 2030. In a review of the flourishing literature on the MSR, Osorio et al., 2020 report that cancellations estimates vary from 1.2 to 13 $GtCO_2$, depending on assumptions about the chosen discount rate and marginal abatement costs. In a model covering the full EU-ETS with a discount rate of 3% (risk-free rate), Quemin and Trotignon, 2019b find 10$GtCO_2$ of permits cancelled by 2050. Besides, Perino, 2018 point out that overlapping policies may affect and strengthen the EU-ETS emissions cap *via* the cancellation mechanism (it «punctures the waterbed effect»).

Beyond the effective decrease in the supply of permits, studies highlight that firms' expectations and planning horizon play a key role in determining impacts of the MSR, *via* banking behaviors. For instance, Tietjen, Lessmann, and Pahle, 2020 attribute the recent price surge to risk-averse firms building a permit bank in order to hedge against the increased ambition of the EU-ETS. Moreover, Friedrich et al., 2019 point out the role of (financial) market participants in the upward price trend, and find that the anticipation of the new reform has triggered market participants into speculation. These result question the ability of the MSR to stabilize prices in the long-run, as it may add another layer of uncertainty to an already complex regulatory environment (Richstein, Chappin, and Vries, 2015).

1.5 Phase 4 reform and future challenges

Supply-adjusting measures put in place during Phase 3 pursued the implicit objective of raising short term EUA prices. In turn, a choice was made to follow a static, aggregate

[27] https://ec.europa.eu/clima/policies/ets/reform_en

supply/demand logic. The MSR, by puncturing the bank when too voluminous, goes indeed against the original inter-temporal trading logic of a quantity regulation. The price surge observed in 2018 seems to confirm the success of this logic, at least in the short run.

Yet, the second objective of the MSR, namely stabilizing prices, is left unresolved. Price movements seem to be due, for a large part, to «market sentiment», studies highlight, namely market actors' expectation of a more ambitious climate policy and future permit cancellations. The price reaction greatly anticipated the MSR's action indeed, raising the limits of a direct price/quantity relation in the EU-ETS. Consequently, the challenge is to align the beliefs of market actors for EUA prices to remain at their desired level and limit price volatility. As developed below, Phase 4 reform and EU's post 2021 climate policy implicitly seek this objective.

1.5.1 Increased ambition

Officially, Phase 4 revision pursues the objective of attaining a reduction of 43% of emission reductions relative to 2005 levels, as stated in the 2030 climate & energy framework. Besides measures reinforcing the MSR with a temporarily increased intake rate and cancellation mechanism, the revision also includes an acceleration in the linear reduction factor, going for 1.74% to 2.2% starting in 2021.

Moreover, two funds are to be implemented in order to help energy-intensive industrial sectors and the power sector comply with the new Directive. First, the innovation fund, abounded with 450 million allowances (about 10 bn€depending on the carbon price), will provide grants to innovative projects in the field of low-carbon technologies, carbon capture and storage (CCS), renewable energy generation and energy storage.[28] Second, the modernisation fund, mentioned in Section 1.2.2, will help the 10 lower income countries step away from fossil fuels and carry out energy efficiency measures.[29] The modernisation fund will be funded by 2% of auctions revenue over 2013-20.

Changes in the linear reduction factor and MSR parameters raise the question of their interaction, especially in an uncertain environment. Prospective evaluations have been flourishing in the recent literature in turn (Osorio et al., 2020; Parry, 2020; Quemin et al., 2020). In particular, uncertainty remains about the number of emissions cancelled, especially in the context of imminent German coal phase outs. In July 2020, Germany has indeed passed a legislation to end coal-fired power generation by 2038 at the latest

[28]https://ec.europa.eu/clima/policies/innovation-fund_en

[29]The beneficiary Member States are Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania and Slovakia.

and agreed on a shutdown schedule for individual lignite power plants. Although this decision will undeniably contribute to reaching the 2030 emissions target, doubts remain about the ability of the MSR to absorb the freed up allowances and avoid the carbon price to collapse again. Potential changes to TNAC ranges will be examined as part of the MSR revision in 2021 in turn.

In face of concerns about the second, «stability» function of the MSR, the possibility of implementing a carbon price floor, as is done oversees, has long been discussed by scholars and policy makers. In 2018, french president Macron even proposed to lead the way with a German-French coalition with a price floor of 25-30€/tCO_2. For policy makers, a price floor would strengthen and affirm EU's commitment to reach its ambitious climate-neutrality target and put back carbon pricing at its forefront. Moreover, it would enable member states to lock in revenues from auctions. Importantly, it would also align the price expectation of polluters by explicitly signalling the target cost of carbon. However, it seems that the European Commission's strategy is rather to implicitly take the EU-ETS closer to a taxation system by reducing the bank to a minimum – limiting inter-temporal arbitrages – rather than explicitly implementing a tax on emissions, presumably for political and legal reasons.

1.5.2 European Green Deal

Carbon neutrality. The EU-ETS may also be impacted by the European Green Deal (EGD), presented in December 2019 by the European Commission. As mentioned in Section 1.2.1, the EGD affirms the political will to reach climate neutrality in 2050. A European Climate Law was proposed in March 2020 to write this objective into law. Consequently, the deal will lead to legislative proposals modifying the 2030 climate & energy framework in accordance with the «net-zero» goal, including the EU-ETS directive. In turn, proposals will coincide with 2021 revision of the MSR, including a potential acceleration of the linear reduction factor and MSR intake rates. A study by Marcu et al., 2020 shows that the LRF would need to be increased to 4.3% in Phase 4 indeed, to achieve carbon neutrality in 2050.

However, and since current emissions are already lying far below the cap (by approximately 17% in 2019), it is difficult to predict what the effective cap will look like after 2030. Some stakeholders argued to «rebase» the emissions ceiling to better reflect actual emission levels (Figure 1.6). Moreover, the respective contribution of ETS and non-ETS sectors to the climate neutrality target is still unclear under the EGD, and raises the question of a «sunset clause» for the EU-ETS. Indeed, reaching zero GHG emissions in the power and industrial sectors alone seem unrealistic. Consequently, the EGD raised the inclusion of other sectors in the mechanism, such as maritime transport (shipping), road transport and buildings. Evaluation and practical modalities of such an increase in the scope of the EU-ETS are yet to be studied.

Border Carbon Adjustments. One major element of the EGD is the implementation of a carbon border adjustment mechanism (BCA). The main goal of a BCA is to prevent direct carbon leakage, which can materialize in two ways. First, operational leakage relates to industrial firms relocating their production and importing from countries with less ambitious carbon pricing policies. Second, investment leakage happens, in the long run, when firms increase their production capacity in low-carbon-price countries (Zachmann and McWilliams, 2020). Both forms of leakage lead to an increase in imported, carbon-intensive goods. Although there has been a lack of empirical evidence for carbon leakage in Europe (Dechezleprêtre et al., 2019), the strengthening of climate ambition set by the EGD and certain increase in the near-term carbon price may impose a competitive burden on European industrial sectors in the world market.

In turn, a carbon adjustment mechanism enables to restore the terms of trades in the presence of a unilateral policy that is detrimental to competitiveness. Figure 1.9 outlines the operation of a BCA. If A is the industrial sector operating in the EU and at risk of carbon leakage (e.g. steel production), imports of steel by A from the rest of the world must bear the same price of carbon as the domestic carbon price (i.e. the EUA price on the EU-ETS). This way, and everything else equal, A is indifferent from producing domestically or relocating its production outside Europe. Moreover, it is no longer profitable for the EU to import Chinese steel relative to European's.

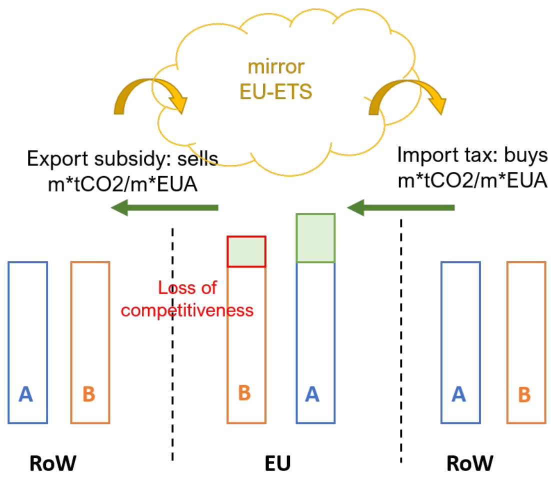
Note however that a single import tax is not sufficient, as A's would suffer a competitive loss in the world market, if not for the additional export subsidy. To ensure that the terms of trade are unchanged by the BCA, and that steel trades at the world price, an export subsidy must accompany the import tariff indeed. A's European market in therefore protected by the BCA, without suffering a competitive loss in the rest of the world.

In practice however, several aspects complicate the implementation of a BCA. First, the carbon adjustment may be detrimental to downstream sectors that use upstream products protected by the carbon adjustment (e.g. steel) as inputs. As Figure 1.9 shows, the downstream sector B has to bear the additional cost of procurement because of the carbon tariff imposed on its suppliers, without being protected by an export subsidy itself. In such a case, sector B would find it more profitable to relocate its production capacity outside the EU to avoid the extra charge, leading to downstream carbon leakage in turn.

The extent to which downstream sectors would be exposed to a risk of carbon leakage is unclear, especially because of the lack of empirical evaluations. Zachmann and McWilliams, 2020 argue that lessons can be drawn from the steel and aluminium tariffs implemented in the US in March 2018. A White House report[30] found that domestic steel capacity did not increase after the tariff came into force, but that imports of certain steel products significantly increased. In one year indeed, imports of steel nails, tacks, drawing pins, corrugated nails, staples and similar articles increased by 33%, while imports of aluminium wire, cables, plaited bands and similar increased by 152%.

However, this experience has to be nuanced. In France for instance, a financial support is already allocated to energy-intensive sectors that indirectly bear the carbon price on the EU-ETS, through their electricity purchases. The «indirect carbon compensation» scheme, which is indexed on the carbon price and represents 279.5 million € in 2020 (+ 163% relative to 2019), helped the steel and cement industries, among other, face higher electricity costs.[31]

FIGURE 1.9: BCA mechanism with a mirror scheme



Note: Inspired from Christian de Perthuis's presentation at the Florence School of Regulation, 2019. A represents the upstream sector (e.g. steel producer) and B the downstream sector using A as an input (e.g. car manufacturer)

A second point of debate relates to the interaction between the free allocation of allowances to industrial companies and the BCA. The benchmarking allocation method, which still represents about 30% of industrial permits according to the EC, already accounts for a risk of carbon leakage (see Section 1.4.1 for details). In turn, superposing a BCA on top of the existing mechanism would result in subsidizing polluting industries twice, by means of (i) free permits and (ii) the export subsidy. This might be detrimental

[30] https://www.whitehouse.gov/presidential-actions/proclamation-adjusting-imports-derivative-aluminum-articles-derivative-steel-articles-united-states/

[31] https://www.ecologique-solidaire.gouv.fr/sites/default/files/Rapportage_couts_indirects_2019.pdf

to the environmental objective set by the EGD, and dampen firms' incentive to carry out technological progress (the Porter hypothesis). Ideally, the BCA would then replace free allocation in the EU-ETS, to protect industries at risk of carbon leakage while preserving the price signal on the domestic market.[32] This is the option put forward by the French authorities over a 10-year transition period.[33] Besides, implementing a BCA requires to know the carbon content of every imported product, which seems unrealistic. First, companies may be reluctant do disclose their entire value chain, Zachmann, 2015 point out. Second, the benchmark experience demonstrated how time-consuming the associated expertise can be (consultations lasted for 2 years). One option put forward by recent consultations led by the EC is to start with pilot sectors that mostly import homogeneous, little-transformed products, like steel and cement. For these sectors, carbon-content information from product benchmarks could be used, although an update would have to be eventually envisaged as benchmarks rely on 2009 data.

Finally, legal matters remain a major implementation barrier. First of all, the BCA has to comply with the General Agreement on Tarifs and Trade (GATT) rules. Specifically, the mechanism must be non-discriminatory, namely imported goods must be treated equally to equivalent goods produced in the EU. In case of litigation indeed, it is necessary to demonstrate that (i) the EU-ETS has an effect equivalent to a tax on European goods, (ii) the extra charge imposed to foreign goods does not exceed the carbon price on the EU-ETS and (iii) export subsidies perceived by European companies do not lead to unfair competition in the domestic market, excluding taxes. Reports also highlight that the EU must be able to prove that the BCA is solely implemented for environmental purposes.

Consequently, one option for a WTO-compatible BCA would be to include foreign producers in the EU-ETS. However, this would require to revise the EU-ETS cap, disturbing the fragile supply/demand equilibrium. Therefore, the French Authorities are in favor of a «mirror scheme», where importers would surrender specific, non-tradable carbon allowances. This way, the tariff would be indexed on the actual EUA price – conforming to GATT rules – without have to reform the EU-ETS directive. A default carbon content could also be provided to start with, leaving the liberty to the importer to prove it wrong.

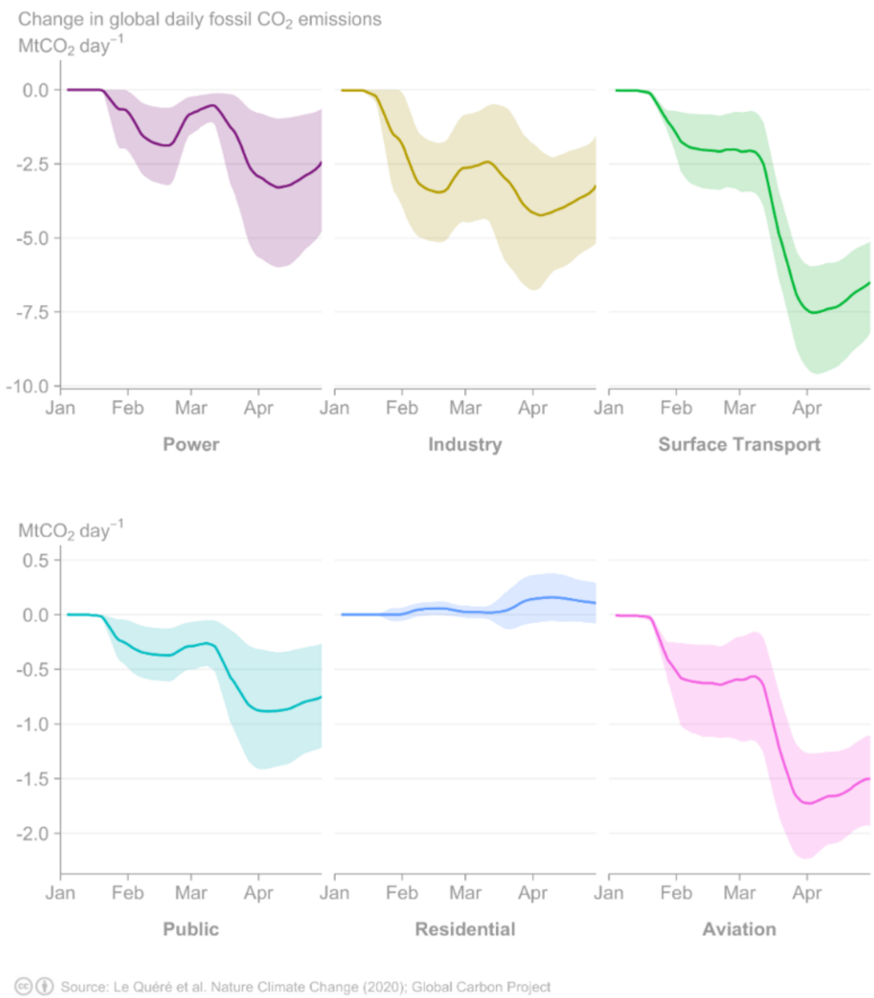
[32] Steel representatives push for preserving free allowances: see the feedback of the European Steel Tube Association (ESTA) on the BCA.

[33] See stakeholder feedback received on the BCA : https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12228-Carbon-Border-Adjustment-Mechanism/feedback?p_id=7587254

1.5.3 Covid-19

Last, the Covid-19 outbreak will surely impact the EU-ETS. The global carbon project estimated that daily global CO_2 emissions decreased by 17% by early April 2020 compared with the mean 2019 levels, mainly from the slow down of the transport sector (see Figure 1.10). In a short lock-down scenario, the impact on 2020 emissions could amount to a 4% decrease. Therefore, the crisis is putting the MSR at its first real test: will it be able to absorb the resulting allowance surplus, that harmed the EU-ETS so much during the 2009 financial crisis ?

FIGURE 1.10: Effect of Covid-19 on emissions



Looking at EUA prices, the market seems to resist the crisis so far (Figure 1.11). After the announcement of the first lock-downs in early March, prices dropped suddenly but quickly recovered to reach their 2019 levels. This questions the correlation between the quantity of permits on the market and allowance prices, since the action of the MSR has a two-year lag. It also suggests that anticipations of market actors would be an important factor to explain price formation. First, the expectation of a quick recovery could explain the price surge, as the EU announced a major recovery plan of €750Bn to support the most affected countries and sectors. Moreover, political communications of the EU have recently put climate policy at the forefront, despite the economic crisis, which could explain the price resistance.

However, EUA price are strongly correlated with oil prices (Figure 1.11), suggesting that macroeconomic conditions and demand for pollution are important determinants of price formation. In turn, doubts can be raised about the stability function of the MSR, since it does not adjust the supply instantaneously. EUA prices have been, although higher than expected, extremely volatile indeed, which could have damaging effect on investment incentives for risk-averse firms.

FIGURE 1.11: Effect of Covid-19 on EUA prices

(A) EUA prices

(B) Crude WTI oil prices

Note: Source Inter-Continental Exchange, DailyFx.

1.6 Conclusion

In the first chapter of this dissertation, we provided a historical overview of crises and reforms undergone by the EU-ETS since its implementation to this day, and outlined future challenges it will face in Phase 4. In particular, we pointed out that the credibility of the mechanism was strongly undermined in its second phase, after EUA prices plunged in 2008 and stagnated over the following decade. The lively criticism addressed to the EU-ETS has demonstrated that the mechanism is, above all, judged on the price levels it delivered, despite satisfactory emissions reductions. Emissions targets have always been attained before schedule indeed. This paradox reveals that the implicit goal of the EU-ETS, namely headlining the EU as a pioneer in climate policy beyond the scope of the industrial sector, predominates a mere price discovery function.

As such, two major reforms were conducted at the beginning of Phase 3, which primarily sought to raise near-term carbon prices. Importantly, they were designed assuming a valid, static price/quantity relationship in the EU-ETS, and therefore aimed at cutting back the permit surplus accumulated during Phase 2. Specifically, the 'backloading' measures resulted in deferring auctions and the MSR was implemented to stabilize the instantaneous amount of permits in circulation. Moreover, the MSR was equipped with a cancellation mechanism which is expected to cut back a large amount of permits from auction starting in 2023. We emphasize that, interestingly, these reforms contrast with the theoretical mechanism of inter-temporal permit trading as they alter firms' emissions planning, thus relaunching the debate on the 'right' amount of banking in the EU-ETS.

The 2018 price surge was interpreted by policy makers as the successful materialization of supply-adjusting reforms conducted earlier. Does this imply that the EU-ETS should be managed following a static supply/demand logic yet ? There are several points to be clarified before coming to this conclusion indeed. First, the price increase observed in summer 2018 greatly anticipated action by the MSR, and second, reforms did not resolve the price volatility issue. Therefore, this suggests that market 'sentiment' is an important price driver in the EU-ETS, and calls for a clear and transparent communication of price and environmental objectives. Announcing a clear price target being contrary to the quantity instrument logic, the European Commission decided to reinforce the environmental objectives in Phase 4. In particular, the 'carbon neutrality' target has been heavily used in recent communication, to reinforce the credibility and ambition of the EU-ETS. The mechanism is in turn bound to another reform in 2021, in a difficult context of Covid-19 crisis and the large upcoming wave of coal phase outs. An opportunity to put the MSR at real test, although repeated reforms might be detrimental to its price stability objective.

Chapter 2

Emissions trading with transaction costs

This chapter is the result of a collaboration with Simon Quemin and Marc Baudry

* * *

2.1 Introduction

Stemming from the seminal works of Coase, 1960, Crocker, 1966a and Dales, 1968b and later formalized by Montgomery, 1972, emissions trading has become pivotal in the environmental and climate change mitigation regulatory toolbox.[1] Purportedly, comparative advantages of this instrument include cost effectiveness, modest information requirements for the regulator and a political-economy lever by means of the initial distribution of emissions permits. The collective optimum can in principle be decentralized via the market price: given a total supply of permits, the same price level obtains in equilibrium and abatement efforts are rerouted to firms with lowest marginal abatement costs irrespective of their initial allocation as a result of market participants' endeavor to ferret out least-expensive abatement sources.

As two of the concept's founding fathers recognize in the opening quotes, however, a variety of barriers to trading – usually grouped under the term of transaction costs – can drive a wedge between theoretical and practical market outcomes. In practice, indeed, frictions of various types are acknowledged to be pervasive as the empirical literature on permit markets attests (e.g. Carlson et al., 2000; Gangadharan, 2000; Hahn and Stavins, 2011; Jaraitė-Kažukauskė and Kažukauskas, 2015; Venmans, 2016; Karpf, Mandel, and Battiston, 2018; Naegele, 2018; Cludius and Betz, 2020) and, more generally, there are costs associated with trading in financial markets (e.g. Gârleanu and Pedersen, 2013; Dávila and Parlatore, 2020, and references therein). We corroborate these findings with a descriptive analysis of trading and compliance patterns in the second phase of the EU Emissions Trading System (2008-12) which also suggests the existence of transaction costs. This echoes one conclusion of Hintermann, Peterson, and Rickels, 2016 who

[1] Medema, 2020 offers an excellent overview of the historical context and impacts of the Coase theorem. See also Deryugina, Moore, and Tol, 2020 for a recent review of its applications to environmental problems.

review the literature on price and market behaviors in Phase II of the EU ETS: they highlight that transaction costs are a key factor that impinge on price formation, notably its level, and can explain persisting differentials in marginal abatement costs across firms.

Yet, surprisingly, the prevalence of transaction costs and their implications for market outcomes as well as for policy design, evaluation and implementation are largely ignored in the theoretical literature on permit markets, with only a few exceptions discussed below.[2] In this paper, we seek to remedy this gap. Specifically, we incorporate trading costs in an otherwise archetypal emissions trading model to formally analyze how they impact the market equilibrium. We further calibrate the model to observed transactions in Phase II of the EU ETS to offer an illustration based on a relevant real-world example. As we shall see, not only is such a framework better equipped to conduct finer-grained ex-post analyses of firms' trading and compliance behaviors, but it also constitutes a more realistic basis for ex-ante assessments of supply-side management policies, a regular feature in the hybrid ETSs of today.

We articulate three contributions to the literature. To motivate our analysis further, we begin by exploring the universe of annual transactions in EU ETS Phase II, our policy environment in this paper. Data is available at the account (installation) level but we consider the firm as the relevant decision-making unit for our analysis and we concentrate on inter-firm trading.[3] To aggregate the data at the firm level and remove intra-firm permit reallocations, we develop a consolidation methodology matching each installation to a parent company building on an iterative search procedure for duplicates in the accounts' information fields. We then utilize the consolidated dataset to scrutinize firms' annual trading and compliance behaviors. The consolidation methodology and the description of observed firms' market behavior constitute our first contribution to the empirical literature on the EU ETS.

We find evidence of autarkic compliance and signs of impaired trading, i.e. some gains from trade go unrealized at both the extensive and intensive margins, see Ellerman, Convery, and Perthuis, 2010, Martin, Muûls, and Wagner, 2015 and Schleich et al., 2020 for similar descriptive results.[4] At the extensive margin, about a third of firms did not

[2]In a related context, see Dixit and Olson, 2000 and Anderlini and Felli, 2006 for formal analyses of Coasean bargaining in the presence of transaction costs.

[3]A firm typically owns several regulated polluting sites and can redistribute allocated permits across sites based on their realized emissions, i.e. it can potentially achieve compliance without effectively trading on the market. Here, we implicitly assume that the costs of intra-firm transfers are negligible compared to those of inter-firm trading. In our dataset, intra-firm transfers represent 27% of all cross-account flows in Phase II.

[4]Other studies have provided indirect evidence of transaction costs relying on surveys and interviews with firms' managers (e.g. Venmans, 2016; Heindl, 2017) or analyzing transactions with network theory

trade at all on a yearly basis. Autarkic firms are mostly small (in terms of size of emissions or number of installations) representing 9% of regulated emissions and often hold excess permits w.r.t. realized emissions. At the intensive margin, active firms engaged in trading infrequently (typically a few times per annum) and only for sufficiently high volumes, suggesting that marginal abatement costs are not equalized across firms in equilibrium. Stifled trade at both margins points us to the prevalence of both fixed and variable transaction costs (see also Stavins, 1995; Singh and Weninger, 2017).[5]

Our second contribution to the literature is theoretical in nature. We enrich a standard static and deterministic permit trading model by introducing both fixed and proportional trading costs.[6] The fixed cost impacts firms' decisions to take part in the market (extensive margin) while the proportional cost further affects firms' trading choices by driving a wedge between their marginal abatement costs (intensive margin). In our equilibrium framework, the permit price and firms' participation in and extent of trading are determined endogenously, and they depend on the given trading costs and firms' characteristics (i.e. abatement costs and permit allocations, where we let some firms be initially overallocated).[7] Importantly, this framework enables us to study when a market equilibrium exists and if so, how it is achieved.

Tracking trading cost impacts through buyer-seller interactions and resulting market prices, we can analyze the sensitivity of the market equilibrium to changes in the trading costs and firms' initial allocations. While an increase in trading costs always reduces cost effectiveness and the volume of trade, its price effects are ambiguous and non-monotonic in general as they depend on its relative impacts on the supply and demand sides of the market (i.e. ultimately the distributions of firms' characteristics). As a rule, we find that trading costs are generally conducive to higher price levels when the (theoretical) frictionless market price is 'low', and vice versa. Similarly, the price increase following a reduction in the total number of permits can be amplified or dampened by the presence

tools (e.g. Borghesi and Flori, 2018; Hintermann and Ludwig, 2018; Karpf, Mandel, and Battiston, 2018). See Section 2.2.1 for more details.

[5]In the words of Stavins, 1995 «transaction costs can take one of two forms, inputs of resources–including time–by a buyer and/or seller or a margin between the buying and selling price», i.e. fixed and variable costs. More concretely, fixed entry costs can compound exchange membership fees with other resources invested in operating a trading desk, monitoring the market and defining a trading strategy. Variable costs can comprise search, information, brokerage, intermediation and consultancy costs inter alia.

[6]We solely focus on those transaction costs entailed by (or conditional on) permit trading, hence termed trading costs for short. See Section 2.2.1 for a brief overview of other types of transaction costs.

[7]Following the related literature (e.g. Stavins, 1995; Singh and Weninger, 2017) we take the trading costs as exogenously given, but we discuss in Section 2.2 how they may emerge in practice. As a notable exception, see Liski, 2001 for microfoundations, i.e. a formal treatment of trading costs endogenously arising and evolving over time as a function of the market size and the initial distribution of permits among firms.

of trading costs. This hinges on a distribution effect (the overall impact on net permit demand, holding the price constant) and a price effect (the relative price elasticity of net permit demand with vs. without trading costs) which are generally countervailing. To gain additional insight into the market impacts of trading costs, we then illustrate our theoretical results with analytical and numerical examples for different distributions of firms' characteristics. These show that both the price level and increase (due to a lowered amount of permits) are more often higher with trading costs than without.

The benchmark framework to analyze the impacts of transaction costs in markets permit has been developed by Stavins, 1995 and extended by Montero, 1998.[8] Crucially, however, this is not an equilibrium framework and the market price is taken as exogenously fixed. That is, Stavins and Montero study the impacts of trading costs on an individual firm's emission and trading choices at the margin but do not formally characterize the market price impacts nor how firms self-select into costly trading in the first place as we do in this paper. As a result, our framework sometimes leads to different results, e.g. market outcomes are sensitive to the initial allocation of permits even with constant marginal trading costs. More recently, Singh and Weninger, 2017 have developed a similar equilibrium framework in the presence of fixed or proportional trading costs, alternatively.[9] But in their model, firms are ex-ante identical and differ only in idiosyncratic productivity shocks, the main motive for permit trade.[10] Our analysis is hence different in nature as we choose to focus on what we believe to be the more practically relevant case of ex-ante heterogeneous firms (see Bernard et al., 2012 and Melitz and Redding, 2014 in the more general context of international trade in goods).

This brings us to our third contribution to the literature, which exploits firms' heterogeneity in abatement costs and allocations allowed by the model. Specifically, we utilize the universe of yearly allocations, emissions, transactions and prices in EU ETS Phase II to discipline the calibration of model parameters and the selection of practically relevant trading costs values. We propose a selection criterion minimizing the total number

[8]Specifically, Montero, 1998 offered an extension of Stavins' analysis in the form of uncertainty on trade approval and provided further insights with numerical simulations. Moreover, Cason and Gangadharan, 2003 used a laboratory experiment to test (and confirm) the main results implied by Stavins' theory.

[9]Similarly, in a permit trading model with transaction costs, Constantatos, Filippiadis, and Sartzetakis, 2014 show how permit allocation can be used as a strategic trade instrument on the product market even without market power.

[10]Singh and Weninger invoke an argument in the spirit of Samuelson's Factor Price Equalization theorem whereby in mature ETSs productivity shocks should be the main drivers for trade. While this simplifies their analysis, which accounts for the interaction with the product market, it is our contention that existing ETSs are still far from mature in this respect, and therefore that heterogeneity in abatement costs and allocations remains the main motive for trade (a fortiori in EU ETS Phase II, our policy environment in this paper).

of sorting errors (i.e. discrepancies between firms' market participation and net market positions in the model vs. the data) and their dispersion across error types (measured by Shannon's entropy).[11] Respectively, we find fixed and proportional trading costs in the order of 5-20 k€ per annum and 0.5-1.5 € per permit traded (or 3-11% of the permit price) across years. Relative to zero trading costs, the selected trading costs reduce the total number of sorting errors by 40%, their dispersion by 160%, and can rationalize 70% of autarkic compliance cases. Our model calibration exercise thus shows how accounting for trading costs can be important for ex-post policy evaluation. It also provides first-pass estimates of trading costs in the EU ETS where related empirical studies have gathered anecdotal or indirect evidence (e.g. Venmans, 2016; Karpf, Mandel, and Battiston, 2018) or used econometric estimation techniques e.g. Medina, Pardo, and Pascual, 2014; Jaraitė-Kažukauskė and Kažukauskas, 2015; Naegele, 2018. Interestingly, or perhaps reassuringly for our approach, we obtain similar orders of magnitude as the latter studies.

Finally, we leverage our calibrated model to compare the quantitative results that a modeler or regulator would obtain in assessing the total costs the ETS imposes on firms or the market price impacts of additional supply-curbing policies, depending on whether or not transaction costs are accounted for. In our setting, extra compliance costs resulting from incurred trading costs and foregone efficiency gains are in the order of 7% of the compliance costs in a scenario where transaction costs are ignored. In a similar vein, we find that the price increase following a reduction in the total number of permits would be underestimated if one does not account for transaction costs. This is because in our setting some firms holding excess permits do not offer them for sale due to the transaction costs, implying that the price increase is inefficiently large. Specifically, we find an underestimation factor of two for a one-sixth reduction in the total cap, with variations in size of up to 30-40% depending on its incidence on firms.

The remainder of the paper is organized as follows. We close this section with a brief literature review to contextualize our results and some limitations of our analysis. Section 2.2 provides further background on transaction costs and trading patterns in EU ETS Phase II. Section 2.3 develops the emissions trading model in the presence of fixed and proportional trading costs, and provides analytical and numerical illustrations. Section 2.4.1 describes the calibration of the model to EU ETS Phase II data and the selection of trading costs. Section 2.4.2 utilizes the calibrated model to evaluate and compare

[11] Our calibration methodology also replicates observed annual prices but this cannot be the key selection criterion as it is not robust enough in itself for our purposes e.g. Carlson et al., 2000 and price depends on a variety of other factors our model does not explicitly account for (but which we control for). Additionally, we focus more on the extensive margin than on the intensive margin impacts of trading costs, as the latter are hard to quantify meaningfully without precise abatement cost data.

supply-tightening policy impacts in the presence vs. absence of trading costs. Section 2.5 concludes. An Appendix collects analytical derivations (2.6) as well as details on the consolidation methodology (2.7) and calibration results (2.8).

2.1.1 Contextualization

Before proceeding further, we wish to acknowledge some limitations of our approach in order to put into perspective our modeling choices and results. These relate to temporal, behavioral and institutional factors which may impinge on firms' participation in and extent of inter-firm trading but are not formally treated in the present framework.

Because these interrelated factors can distort and impair inter-firm trading incentives relative to an idealized market environment without frictions, our approach, by exclusively focusing on (pecuniary) transaction costs, may overstate the latter's impacts. That said, the literature on permit markets generally ignores these factors or, more exceptionally, treats them individually as we discuss below. Against this background, we believe that our formal equilibrium analysis of the impacts of transaction costs and underlying mechanisms at play constitutes a welcome addition to the literature, as a fist step towards a more comprehensive framework. Relatedly, our model calibration in Section 2.4.1 can be thought of as capturing the aggregate impact of these various factors, rather than the exclusive impacts of transaction costs.

Banking and borrowing. Firms generally have some leeway in banking issued permits for future use or borrowing future permits for present use. While this flexibility margin reduces trading incentives, it is not sufficient to rationalize autarkic compliance and one should still expect some potential profits from inter-firm trading. For instance, some firms may still find it too costly to solely abate internally (e.g. when borrowing is restricted) while others may not want to bear the opportunity cost of not selling at least some of their excess permits. Again, this points us towards the prevalence of transaction costs, or other biases discussed below. In this context, intertemporal trading can even serve as a substitute to costly spatial trading. As a case in point, in the US Acid Rain Program (ARP), Toyama, 2019 numerically estimates significant trading costs, in a range of 15-35% of the market price per permit traded, which in turn imply excess banking and less dispersed emissions as a result of lower inter-firm trades relative to an idealized counterfactual scenario without trading costs.[12]

[12]Specifically, buyers (resp. sellers) face a lower (resp. higher) banking incentive as transaction costs drive a wedge between firms' marginal abatement costs – and ultimately a shadow value higher (resp. lower) than the permit price. Thus, aggregate banking could in principle be higher or lower than in the first best.

Except in Toyama, 2019, however, the interplay between trading and banking decisions with transaction costs is seldom accounted for.[13] And more generally, to investigate specific policy impacts, the temporal dimension of permit markets is often set aside in both numerical and analytical approaches. For instance, Fowlie, Reguant, and Ryan, 2016 develop a dynamic oligopoly model to numerically compare firms' entry/exit decisions and capacity investments on the product market under different permit allocation regimes, but do not consider banking provisions to isolate the allocation impacts. Similarly, to assess cost savings and health impacts under the ARP, Chan et al., 2018 use a static model of compliance choices (fuel switch, permit purchase, scrubber installation) to sidestep the complexities associated with modeling banking and permit purchase as an option to install a scrubber or fuel switch at a later date.[14] Both approaches are therefore likely to overemphasize the spatial trading dimension.

As in Singh and Weninger, 2017, we develop a static permit trading model in order to be able to derive and exploit novel analytical results on the equilibrium impacts of transaction costs. Since the temporal dimension is not formally treated, our calibration exercise should in turn be seen as providing upper bounds for the transaction costs and their impacts.[15] However, we take firms' observed banking dynamics as a given to adjust their allocations and mitigate this limitation. Additionally, we wish to underline that the temporal dimension is also likely to be subject to other specific costs and limitations, which relate to the other biases discussed below. It is indeed difficult to elicit firms' degree of intertemporal optimization (e.g. Ellerman, Marcantonini, and Zaklan, 2016b; Hintermann, Peterson, and Rickels, 2016) and there is evidence of limited farsightedness or biased beliefs (e.g. Chen, 2018; Fuss et al., 2018; Quemin and Trotignon, 2019a).[16]

Behavioral biases. Autarkic compliance and stifled trading may also result from behavioral biases. For instance, autarkic firms can be thought of as trading off profits from entering the market with higher associated organizational and decision-making complexity. As heuristics or rules of thumb, autarkic banking and borrowing may thus

[13]Rubin, 1996 already noted that in the absence of quadratic transaction costs or bounds on firms' trading, a dynamic model suffers from indeterminacy as firms' objective functions are linear in traded volumes – thus, optimal banking and trading decisions cannot be identified. For instance, **Koll19**; Kollenberg and Taschini, 2016 introduce quadratic transaction costs to have a well-defined optimization problem and simplify the derivation of the equilibrium in closed form (relative to fixed costs, as they do not affect firms' participation in trading).

[14]Similarly, Carlson et al., 2000 compute long-run gains from trade in a steady state of the ARP, bypassing the issue of modeling intertemporal decisions by taking firms' banking behavior as given.

[15]Similarly, Jaraitė-Kažukauskė and Kažukauskas, 2015 and Naegele, 2018 employ static frameworks for their econometric estimations of transaction costs and their impacts on firms in the EU ETS.

[16]In the ARP, Chen, 2018 shows that it took time for firms to form and adapt their beliefs about future price levels, leading to biased banking strategies especially in the early stages of the program. In the EU ETS, Quemin and Trotignon, 2019a show how rolling finite planning horizons help reconcile the observed aggregate banking dynamics with discount rates implied from futures' yield curves.

constitute viable, if not rational, strategies when deemed to perform satisfactorily well relative to more complex and thus costly procedures (e.g. Baumol and Quandt, 1964; Simon, 1979; Radner, 1996; Gigerenzer and Selten, 2003).[17] That is, firms may have to make compromises as they juggle with other objectives, perhaps perceived as more essential. For instance, based on interviews with plant managers, Venmans, 2016 notes that some perceive the ETS as a command-and-control type of policy, especially when commodity trading is not part of their firms' core business – in this case, the carbon liability is typically dealt with by the accounting department.[18] In other words, firms may rather seek to attain compliance with the least additional complexity and disruption to their routine operations than maximize profits from permit trading.

More generally, an insight from behavioral economics is that firms are likely to be subject to endowment effects w.r.t. their permit holdings, which can also frustrate trading. Indeed, «endowment effects are predicted for property rights [...] such as transferable pollution permits» (Kahneman, Knetsch, and Thaler, 1990) because «losses are weighted substantially more than objectively commensurate gains in the evaluation of prospects and trades» (Tversky and Kahneman, 1991). This is confirmed by Murphy and Stranlund, 2007 and Venmans, 2016 with laboratory experiments and interviews, respectively. As a result, firms' willingness to pay for extra permits is larger than their willingness to sell excess permits, implying that differences in firms' marginal abatement costs can persist post trading independently of transaction costs.[19] Relatedly, we note that other institutional factors may also affect firms' compliance decisions, e.g. the level of trust in institutions as uncovered by Jo, 2019.

Intermediaries and trading venues. We further wish to acknowledge that our framework restrains the compliance choice space for firms to a blunt 'autarky vs. trading' and that it does not account for the involvement of non-regulated entities, typically banks and intermediaries. That is, it does not formally distinguish between the different available trading platforms (e.g. auctions, exchanges, over the counter), products, partners

[17]In the EU ETS for instance, Cludius and Betz, 2020 observe that small firms are more likely to pursue a single, simple trading strategy compared to larger, more professionalized firms that are more likely to interact with different partners on different exchanges. Relatedly, Hortaçsu and Puller, 2008 explain that large power producing firms in Texas perform closer to profit maximization than smaller ones as a result of fixed costs of establishing and maintaining sophisticated auction bidding strategies, with clear economies of scale.

[18]Similarly, Martin, Muûls, and Wagner, 2015, Liu, Guo, and Fan, 2017 and Schleich et al., 2020 note that some firms perceive the EU ETS as a pure compliance instrument rather than as a compliance market. Relatedly, Jaraitė, Convery, and Di Maria, 2010 highlight that small firms' reluctance to sell excess permits may be explained by a cautious inclination to keep and use permits for future compliance only rather than by transaction costs per se.

[19]Importantly, Kahneman, Knetsch, and Thaler, 1990 show and underline that, in a trade setting, transaction costs alone are not sufficient to explain undertrading – endowment effects also play a role.

or combination thereof that firms may possibly select.[20] Relatedly, it only represents trading as a way of minimizing compliance costs, but it ignores other motives to trade such as hedging or generating additional revenues (e.g. Schleich et al., 2020).[21] Yet, we note that these aspects structure the trading network, leading to hubs and concentration in trade (e.g. Borghesi and Flori, 2018; Karpf, Mandel, and Battiston, 2018).[22] Cludius and Betz, 2020 also document the increasing engagement of banks in the EU ETS and their liquidity-enhancing and trade-facilitating roles (e.g. account manager, hedging partner). This highlights the need to understand how market microstructure shapes transaction costs, which may decrease over time as markets become more mature e.g. Joskow, Schmalensee, and Bailey, 1998.

Finally, there exists evidence from bid-ask spreads and anomalies in cost-of-carry relationships that price informativeness might be hampered in the EU ETS, see e.g. Friedrich et al., 2019 for a review. However, in our deterministic framework, we cannot analyze how informational efficiency is affected by the costs of trading and refer the reader to Dávila and Parlatore, 2020 for a formal analysis in financial markets. In fact, we underline that even without transaction costs, informational efficiency is likely to break down as dispersed information cannot be fully aggregated by the market in equilibrium (e.g. Grossman and Stiglitz, 1980). For instance, in a frictionless ETS, Cantillon and Slechten, 2018 demonstrate that the permit price is already not a sufficient statistic when individual abatement costs are private information.[23]

2.2 Background

In this section, we first review the related empirical literature on transaction costs in permit markets. We then analyze transaction and compliance data in Phase II of the EU ETS and uncover stylized patterns in firms' market behavior that point us towards the prevalence of costs associated with inter-firm trading.

[20] As a possible way of accounting for these aspects in an ETS, see Dugast, Üslü, and Weill, 2019 for a model where banks optimally choose to participate in over-the-counter or centralized markets, or both.

[21] We note that compliance-only trading leads to lower effectiveness and market liquidity relative to more active trading strategies that are more likely to enable learning and thus to reduce information and search costs, an aspect our framework does not capture.

[22] Relatedly, in EU ETS Phase I, Balietti, 2016 describes how trading activity by different types of traders is influenced by permit price volatility and vice versa.

[23] For instance, Montagnoli and Vries, 2010 and Crossland, Li, and Roca, 2013 find that the EU ETS's informational efficiency was limited in Phases I and II as a result of thin trading and the existence of both momentum and overreaction in prices, leading to profitable trading strategies even in the presence of transaction costs.

2.2.1 Transaction costs and empirical literature

In practice, firms regulated under an ETS face all sorts of non abatement-related costs.[24] On the one hand, implementation, regulatory and other administrative costs associated with the monitoring, reporting and verification process account for a large share of collateral regulatory costs (e.g. Jaraitė, Convery, and Di Maria, 2010; Heindl, 2017). Since they are one-shot, sunk and faced by all firms, they do not affect compliance costs and choices at the margin and have no bearing on market outcomes. On the other hand, firms incur transaction costs that are associated with their trading activity, the focus of this paper. These include explicit monetary costs such as brokerage and exchange membership fees as well as implicit costs such as search, information, bargaining and internal decision-making costs (e.g. Hahn and Stavins, 2011).[25]

The vast majority of existing empirical analyses of transaction costs is based on the pioneering US cap-and-trade programs or the EU ETS. For instance, they are found to have decreased trading activity in the Wisconsin's Fox River program (Hahn and Hester, 1989) and lowered cost effectiveness by 10-20% in the US lead phasedown program (Kerr and Maré, 1998). Similarly, in the Los Angeles basin (RECLAIM), Foster and Hahn, 1995 analyze trading activity and find that large transaction costs altered market behavior. Gangadharan, 2000 econometrically tests the existence and magnitude of transaction costs, finding that they were most influential in the early years of the program, with a decrease in the probability of trading of 32%. This notwithstanding, Fowlie and Perloff, 2013 cannot reject the Coasean hypothesis that market outcomes were independent of the initial endowments. These observations are corroborated by similar evidence in the ARP where transaction costs were sizable (e.g. Toyama, 2019) but diminished over time as the market developed and firms learned and gained experience (e.g. Joskow, Schmalensee, and Bailey, 1998; Carlson et al., 2000; Schmalensee and Stavins, 2013; Chen, 2018).

In the EU ETS, we separate how the literature has approached the issue of transaction costs into three strands. The first one describes observed trading and compliance behavior through surveys of managers' practices or network-based analyses of transactions. Targeting subparts of the ETS, viz. Belgian (Venmans, 2016), German (Heindl, 2012a; Heindl, 2017), Irish (Jaraitė, Convery, and Di Maria, 2010), Swedish (Sandoff and Schaad, 2009) and manufacturing (Martin, Muûls, and Wagner, 2015) firms, these surveys reveal

[24] A more comprehensive taxonomy of transaction costs and an analysis of their determinants in the context of environmental policy can be found in Coggan, Whitten, and Bennett, 2010. See also Krutilla and Krause, 2011 and McCann, 2013 for a discussion on how to shape policy to lower transaction costs and alleviate their impacts.

[25] For instance, EEX, a major organized exchange platform for the EU ETS, charges 2,500 € for an annual trading license plus ∼3 € per bundle of 1,000 permits (permits are only traded in such bundles on exchanges).

that permit trading is sparse, used mostly for compliance rather than revenue purposes, and often a subsidiary objective in firms' business operations. Analyses of patterns in realized transactions concur to underline the influential role of non-compliance participants in shaping the trading network. For instance, Karpf, Mandel, and Battiston, 2018 bring to light a hierarchical and assortative network structure in which most firms have to resort to local connections or costly intermediaries, the implications of which are then discussed for price discovery, market inefficiency and informational asymmetries.[26] Similarly, Borghesi and Flori, 2018 show that some national registries are more central than others in the network, which is corroborated by a home-country bias in permit trades in Hintermann and Ludwig, 2018.[27]

Further showing that permit trades are not exclusively driven by complementarity in marginal abatement costs, the second strand consists of financial analyses of permit pricing properties. For instance, Palao and Pardo, 2012 find evidence of price clustering in permit futures which they attribute to trading costs. Frino, Kruk, and Lepone, 2010 and Medina, Pardo, and Pascual, 2014 similarly interpret the existence of positive bid-ask spreads. Relatedly, Charles, Darné, and Fouilloux, 2013, Schultz and Swieringa, 2014 and Friedrich et al., 2019 stress that such frictions could partly explain the observed deviations from cost-of-carry arbitrage between spot and futures prices as predicted by theory. This also suggests that some trading cost pass-through in permit prices may exist.

The third strand gathers three econometric analyses specifically focused on transaction costs. Using transactions data for Phase I (2005-2007) and a set of constructed firm-level proxies for (search and information) transaction costs, Jaraitė-Kažukauskė and Kažukauskas, 2015 show that transaction costs have significant impacts on firms' decisions to participate in the market and trade directly vs. indirectly via third parties.[28] They make two important observations. First, there are economies of scale as transaction costs constitute more of an impediment for smaller firms. Second, their proxies also negatively affect firms' extent of trading, suggesting that transaction costs have both a fixed and a variable component. Similarly, Schleich et al., 2020 carry out multivariate analyses of firms' trading behavior (e.g. volume and frequency of transactions, use

[26] In this context, Hintermann, Peterson, and Rickels, 2016 note that the strong presence of intermediaries suggests that transaction costs may be important.

[27] With a cluster-based analysis of transactions in Phase I, Betz and Schmidt, 2016 also show that the bulk of market participants are rather passive traders, with some of these hardly trading at all, and that the most active accounts are to a large extent non-compliance ones (see also Cludius and Betz, 2020).

[28] Transaction costs have a greater impact on firms with a smaller number of installations, less experience with trading (e.g. no in-house trading desk), or no specialized units dealing with emissions abatement. These firms are more likely to trade less frequently or lower volumes, or to trade indirectly, or not to trade at all.

of intermediaries and derivatives) based on their characteristics (e.g. sector, number of employees and installations, net position) over 2005-2015 (see e.g. their Table 13). For instance, Schleich et al. find that firms having a higher net position prior to trading ($|\beta_i|$ in this paper), facing a higher competitive pressure or belonging to the energy sector make a more active and efficient use of the EU ETS.

Finally, to our knowledge, Naegele, 2018 is the only analysis to estimate the magnitude of trading costs, specifically fixed entry costs for both the permit and offset certificate markets. Using transactions data for Phase II (2008-2012), she measures these costs at the firm level as the foregone profits (or opportunity costs) from choosing not to trade.[29] She employs binary quantile regressions, showing that cost distributions are skewed: the median and mean entry costs on the permit market are 7 and 21 k€ respectively (many firms face rather small costs but a few have very high costs). Interestingly, she also finds that firms holding excess permits are relatively more reluctant to trade, highlighting a key asymmetry between short and long firms: the former are under no compulsion to sell while the latter need to be proactive in one way or another (e.g. purchasing permits) in order to achieve compliance.[30]

2.2.2 Anecdotal evidence in EU ETS Phase II (2008-2012)

EU ETS. Every year the EU issues emissions allowances (EUA) through free allocations and auctions, whose total number makes up the cap on emissions. On 30 April of year t, regulated entities are required to remit the equivalent number of EUAs to cover their verified emissions in calendar year $t-1$, one EUA accounting for one metric ton of carbon dioxide equivalent. Options to demonstrate compliance include abatement of emissions (e.g. production curtailment, input substitution, technological upgrade, end-of-pipe measure), purchasing EUAs on the market, and tapping into one's bank of EUAs or next-year's free allocation.[31]

Firms can purchase EUAs on primary markets (i.e. auctions) or trade on secondary markets (i.e. organized exchanges such as ICE and EEX, or over the counter). They may have recourse to registered brokers (i.e. intermediaries) to trade on their behalf. Over Phase II

[29] As in our model calibration exercise in Section 2.4.1, Naegele's estimates of fixed trading costs capture all the frictions, i.e. monetary costs as well as the other factors discussed in Section 2.1.1.

[30] Analyzing firms' trading performances, Liu, Guo, and Fan, 2017 obtain a similar result: short firms are relatively more inclined to trade efficiently than long firms, among which that inclination is more heterogeneous.

[31] Unrestricted banking of issued EUAs is allowed since 2008 while borrowing is de facto permitted by the overlap between the compliance and allocation cycles, but limited. Specifically, free $(t+1)$-vintage allocation starts before year-t compliance is due, entailing that some $(t+1)$-vintage EUAs can be front-loaded to achieve compliance in year t (except across trading phases).

(2008-2012), our period of interest, the yearly averaged total trading volume amounted to 5.6 billion EUAs, about three times the size of the annual emissions caps. Out of these, about 40% were traded over the counter and 60% on exchanges (European Commission, 2015).[32]

Data. Trading activity is recorded in an electronic registry, the EU Transaction Log (EUTL), whose aim is to track the EUA ownership structure across accounts and over time to guarantee an accurate accounting of all issued EUAs. That is, the EUTL records the activity of account holders by keeping track of any EUA transfer, allocation and reconciliation. Unfortunately, it only gathers physical movements on secondary markets so we lack direct information about derivative (i.e. forwards, futures or options) and primary (i.e. auctions) trading.[33] In Phase II Member States only marginally exercised their right to auction up to 10% of all allowances with a hefty 96% realized share of free allocations (European Commission, 2015).[34]

Compliance and transactions are recorded at the polluting site level (one account per installation). As the relevant unit of analysis is the firm (where trading, abatement and compliance decisions can be centralized and coordinated between subsidiary installations) we consolidate the EUTL database from the account to the firm level. Our consolidation methodology and results are described in Appendix 2.7. Our consolidated dataset contains 5,145 firms, binned in six sectors, and transactions between them. The consolidation eliminates intra-firm transfers, which can used by firms as a primary tool to achieve compliance before having to trade on the market. Namely, a firm can pool the EUAs allocated to its installations in a central account and redistribute them back in accordance with installations' realized emissions. Despite that EUAs changed accounts, they have not explicitly been traded. Such intra-firm redistribution represents 27% of the total volume of transfers in Phase II.

Observed firms' behavior. We utilize the consolidated dataset to scrutinize firms' market behavior over Phase II. Figure 2.1 reports individual annual market participation, showing that around a third of firms did not register any trading activity, if not for annual allocation and reconciliation.[35] Note that autarkic firms are relatively small in size

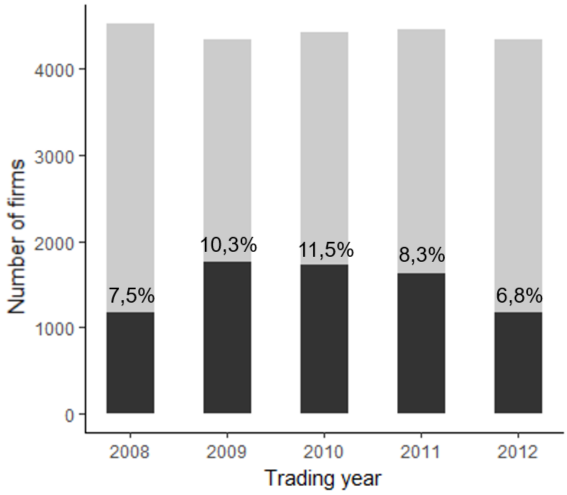
[32]The EUTL data does not specify whether transfers took place on an exchange or over the counter.

[33]Derivative trading represents the biggest share of all transactions but associated data requirements are prohibitive (private data for all operating exchanges would be needed and then linked to EUTL accounts). Because we aggregate EUTL data at the year level we capture the physical settlements of end-of-year derivative contracts but not those trades that clear in later calendar years.

[34]Accounting for auctioned EUAs would also be data intensive as it would require obtaining auctions data from all Member States and then link it to EUTL accounts.

[35]Martin, Muûls, and Wagner, 2015 find a similar share of autarkic firms in Phase II based on interviews for a subset of compliance entities. Martino and Trotignon, 2013 also find evidence of autarkic behavior for 25% of regulated installations based on a similar analysis of transaction and compliance data in Phase I.

FIGURE 2.1: Firms' annual market participation in Phase II



Note: Grey = participation, black = autarky. Slight year-on-year changes in the number of observations are due to plant closures and new entrants. Percentages indicate the proportions of autarkic firms in volume as a share of the total number of distributed permits each year.

(representing only 9% of overall yearly emissions caps on average) and average number of installations (see Table 2.7.1) compared to active firms, whatever their sector. This was to be expected due to economies of scale and could point to the existence of *fixed* entry costs which can preclude some firms from participating to the market.

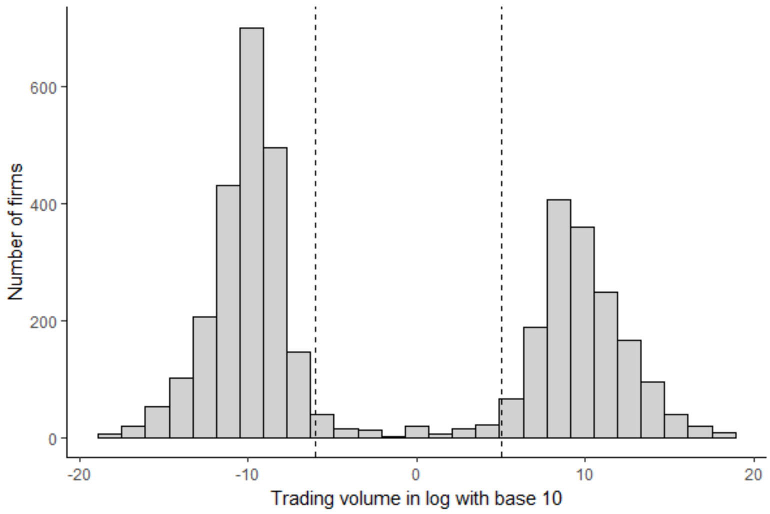
We find that about 80% of autarkic firms received more permits than their verified emissions. They held on to their surplus, de facto banking the entirety of their excess permits.[36] Their private bank at the end of Phase II amounted to 140% of their 2012 endowment on average. The remaining 20% of autarkic firms emitted in excess of their annual allocations and engaged in borrowing. On average, these firms frontloaded 30% of their future allocation on a year-on-year rolling basis.[37] Martin, Muûls, and Wagner, 2015 find similar evidence of autarkic banking in Phase II and unveil a threshold effect: some firms start selling excess permits only when their surplus is large enough. As they argue, this behavior could be rationalized by a fixed cost of trading, controlling for other hedging and precautionary saving motives.

Figure 2.2 depicts the distributions of the volumes of EUA purchases and sales at the firm level in log base 10 for active firms in 2009 (notice that a firm can both buy and sell at different points during the year). We find that active firms rarely engage in trades below some volume cut-off and that they trade infrequently (we record only 4 to 16

[36] Because we do not observe firms' abatement and cannot rule out the implementation of some abatement measures a priori, we cannot distinguish between firms' allocated surplus (i.e. possibly passive banking) and resulting surplus (possibly associated with a proactive abatement and banking strategy).

[37] Ellerman and Trotignon, 2009 and Martino and Trotignon, 2013 also evidence borrowing in Phase I.

FIGURE 2.2: Distribution of participating firms' trading $\log_{10}$ volumes in 2009



Note: The two vertical dotted lines demarcate the 5^{th} percentiles, departing from zero, for the distributions of firm-level $\log_{10}$ volumes of cumulative annual purchases (on the right) and sales (on the left).

transactions per firm per year on average across sectors, see Table 2.7.1).[38] This suggests that a wedge between sellers' and buyers' marginal abatement costs may persist in equilibrium and could point to the existence of variable costs that are *proportional* to the extent (and frequency) of trading.

To summarize, the fact that gains from trade go unrealized at the extensive margin (autarkic firms, Figure 2.1) as well as at the intensive margin (stifled trading, Figure 2.2) is suggestive of the existence of fixed and proportional trading costs.[39] As we will see in the next section in more detail, fixed costs only impact firms' participation in trading (extensive margin) while proportional costs also affect firms' extent of trading (intensive margin).

2.3 Model

We consider a unitary-mass continuum $\mathcal{I}$ of cost-minimizing firms indexed by $i \in \mathcal{I}$ regulated under a market for emission permits. The model is static and assumes away firms' production decisions, i.e. we rule out any incidence or indirect effect of the permit market on the goods markets that the firms serve. In the absence of the permit market, firm i releases u_i units of emission, its unregulated emission level, which can be abated

[38]These observations are in line with the surveys' results of Sandoff and Schaad, 2009 and Heindl, 2012b. For instance, Heindl finds that about half of regulated German firms traded in 2009 and 2010, and two thirds of those that traded did so only once per year, usually as the compliance deadline drew near.

[39]Other behavioral, perceptual and temporal aspects may also hinder trade, as discussed in Section 2.1.1.

at a cost of $C_i(u_i - e_i)$, where e_i are firm i's final emissions after end-of-pipe abatement. As is standard, we assume that $C_i', C_i'' > 0$ and let $C_i : a_i \mapsto \alpha_i a_i^2/2$ with $a_i = u_i - e_i \geq 0$, where we omit the linear term for analytical convenience and without loss of generality up to an innocuous translation of the results. The characteristics α_i and u_i are thus heterogeneous across firms.

Initial permit allocation is also firm-specific and denoted q_i for firm i. We assume that the overall cap on emissions $\mathcal{Q}$ is binding relative to overall unregulated emissions $\mathcal{U}$, that is

$$\mathcal{Q} = \int_{\mathcal{I}} q_i \mathrm{d}i < \mathcal{U} = \int_{\mathcal{I}} u_i \mathrm{d}i,$$

but we allow for overallocation at the firm level, i.e. there exist some firms such that $u_i < q_i$, and we let $\beta_i = u_i - q_i \gtrless 0$ denote firm i's initial permit deficit. In this setting, the two firms' characteristics of interest are thus the α_i's and β_i's which we assume to be distributed over the bounded supports $[\underline{\alpha}; \bar{\alpha}]$ and $[\underline{\beta}; \bar{\beta}]$ where $0 < \underline{\alpha} < \bar{\alpha} < \infty$ and $\underline{\beta} < 0 < \bar{\beta} < \infty$. When firms cannot trade permits with one another, i.e. under autarky, firm i abates $a_i^0 = \max\{0; \beta_i\}$ with $p_i^0 = \alpha_i a_i^0$ the associated autarkic compliance shadow price. In other words, autarkic compliance implies that short firms abate just as much as to cover their permit deficits $\beta_i > 0$ while long firms do not use their surplus permits $-\beta_i > 0$. We next set forth the frictionless benchmark case before introducing fixed and proportional trading costs.

2.3.1 Benchmark: Frictionless equilibrium

Under frictionless conditions (i.e. unrestricted inter-firm permit trading, no trading costs), all firms equate their marginal abatement costs to the prevailing market price p, i.e. $\alpha_i(u_i - e_i) = p$ for any firm i. Note that a feasible market price must be positive as the cap is binding and it can be no larger than $\max_i p_i^0 = \bar{\alpha}\bar{\beta}$ for otherwise no firm would be willing to buy permits. Proposition 1 computes firms' net market positions and efficiency gains from permit trading relative to autarky for any given feasible permit price on the market.

Proposition 1. *Given a feasible market price for permits $p \in (0; \bar{\alpha}\bar{\beta})$, the sets of buying and selling firms are $\mathcal{D}(p) = \{i \,|\, \alpha_i\beta_i > p\}$ and $\mathcal{S}(p) = \{i \,|\, \alpha_i\beta_i < p\}$, and individual efficiency gains from permit trading on the market (w.r.t. autarky) write, for any firm $i \in \mathcal{I}$*

$$G_i(p) = (p_i^0 - p)^2/(2\alpha_i) + p \max\{0; -\beta_i\} \geq 0, \tag{2.1}$$

where $p_i^0 = \alpha_i \max\{0; \beta_i\}$ is firm i's shadow price of autarkic compliance.

Proof. See Appendix 2.6.1. □

Individual efficiency gains from permit trading in (2.1) consist of two non-negative components. The first is common to all firms and proportional to the squared distance in autarky-market prices. Specifically, selling (resp. buying) firms with $p_i^0 < p$ (resp. $p_i^0 > p$) find it profitable to abate more (resp. less) than under autarky and sell surplus (resp. purchase missing) permits on the market. This goes on until all trading opportunities are exhausted, i.e. when marginal abatement costs are equalized between all firms (to the market price). The second component only accrues to those firms that are initially overallocated as they sell the entirety of their initial surplus of permits at the market price at no cost.[40]

Imposing market closure, i.e. $\int_{\mathcal{I}}(u_i - e_i)\mathrm{d}i = \mathcal{U} - \mathcal{Q}$, on top of firm-level optimality conditions defines the frictionless market equilibrium, characterized by the equilibrium price

$$p^\star = (\mathcal{U} - \mathcal{Q}) \, / \int_{\mathcal{I}} \mathrm{d}i/\alpha_i > 0. \tag{2.2}$$

As is well known, $p^\star$ is independent of how the u_i's and q_i's (and thus the β_i's) are distributed among firms. This is the so-called Coasean independence property, i.e. frictionless equilibrium outcomes does not hinge on the initial permit allocation and individual abatement efforts are efficiently reallocated by the market. Note, however, that $p^\star$ depends on the distribution of the α_i's, $\{\alpha_i\}_i$. Specifically, $p^\star$ is proportional to the stringency of the overall constraint on emissions set by the cap, i.e. $\mathcal{U} - \mathcal{Q}$, and the harmonic mean of $\{\alpha_i\}_i$. Therefore, the more skewed $\{\alpha_i\}_i$ towards lower values, the lower $p^\star$ and vice versa.

The individual efficiency gains defined in (2.1) with $p = p^\star$ stem from the cost-effective distribution of the total abatement effort $\mathcal{U} - \mathcal{Q}$ among all firms. Specifically, firm i abates in inverse proportion to α_i, i.e. $a_i^\star = u_i - e_i^\star = p^\star/\alpha_i > 0$, and all firms abate in equilibrium, even initially overallocated ones. We say that the frictionless equilibrium is cost-effective in the sense that (1) all firms are weakly better off participating to the market and (2) marginal abatement costs are equalized between them. As described below, this is no longer the case in the presence of pecuniary costs associated with permit trading.

[40]This component complements the characterization of the effort-sharing gains in Doda, Quemin, and Taschini, 2019.

2.3.2 Equilibrium with trading costs: Characterization

We consider that both permit buyers and sellers incur a market participation cost F and a proportional trading cost T. Following Singh and Weninger, 2017, trading costs are assumed to be common to all firms and exogenously given.[41] That is, firms have to pay a fixed fee F to enter the market and trade permits and T is a mark-up on the permit price p, i.e. buying firms pay $p + T$ per permit purchased, selling firms receive $p - T$ per permit sold.[42]

In the presence of positive trading costs, i.e. $F > 0$ and/or $T > 0$, some firms can be better off under autarky: buying (resp. selling) firms in the frictionless equilibrium can remain buyers (resp. sellers) or prefer not to enter the market altogether (autarkic compliance). We consider that firms make and adjust decisions pertaining to their participation in and extent of trading to minimize individual compliance costs. That is, the only barrier to cost-effectiveness occurs in the form of trading costs (see Section 2.1.1 for a discussion of other barriers). Additionally, we assume that all firms fully acquit their compliance obligations (Stranlund, 2017).

Specifically, when $F > 0$ and $T = 0$, the market outcome is not cost-effective at the extensive margin (some firms do not participate in the market so that some trades that would otherwise be mutually beneficial go unrealized) but it remains cost-effective at the intensive margin (all mutually beneficial trades materialize between participating firms as their marginal abatement costs are equalized). When $T > 0$ and $F = 0$, cost-effectiveness at the intensive margin further drops as participating firms abate in proportion to the actual permit price that they face, i.e. inclusive of the proportional trading cost, which drives a wedge between buyers' and sellers' marginal abatement costs in equilibrium. Specifically, the marginal abatement cost experienced by a buyer exceeds that experienced by a seller by $2T$.

Hence, given a market permit price p and a proportional trading cost $T < p$, firm i will find it profitable to buy (resp. sell) permits on the market provided that $p_i^0 > p + T$ (resp. $p_i^0 < p - T$). Additionally, given a market participation cost $F \geq 0$, a buying (resp. selling) firm i will trade permits on the market when its efficiency gains from

[41] This assumption enables both analytical tractability and model calibration. In practice, trading costs can be firm specific and have non-zero curvature, e.g. convexity is generally considered in finance (e.g. Gârleanu and Pedersen, 2013; Dávila and Parlatore, 2020). To simplify, we assume that variable costs are linear in traded volume and we do not attempt to model how trading costs may arise endogenously (see e.g. Liski, 2001).

[42] In practice, the equilibrium price may also depend on how trading costs are distributed among buyers and sellers. Exogenously fixing how trading costs are shared between firms simplifies analytical computations in our multilateral trading framework, see Quemin and Perthuis, 2019 for a formal treatment of endogenously determined transaction prices in an analogous setting with regulatory restrictions on bilateral permit trading.

permit trading net of both trading costs $G_i(p+T) - F$ (resp. $G_i(p-T) - F$) are positive. Lemma 1 below defines market participation price thresholds for prospective buying and selling firms.

Lemma 1. *Given trading costs F and T and a market permit price $p > T$, it is profitable for firm i to buy permits on the market when $p < \bar{p}_i = \alpha_i\beta_i - T - \sqrt{2\alpha_i F}$. Symmetrically, it is profitable for firm i to sell permits on the market when $p > \underline{p}_i = \alpha_i\beta_i + T + \sqrt{2\alpha_i F}$ if $\beta_i > 0$ or when $p > \underline{p}_i = \alpha_i\beta_i + T + \sqrt{\alpha_i^2\beta_i^2 + 2\alpha_i F}$ if $\beta_i \leq 0$.*

Proof. See Appendix 2.6.2. □

Intuitively, firm i will purchase permits only if the market price is below its autarkic shadow price $p_i^0 = \alpha_i\beta_i$ adjusted for the fixed and proportional trading costs (note $\bar{p}_i$ is decreasing with F and T). Symmetrically, firm i will sell permits only if the market price is above its cost-adjusted autarkic shadow price $\underline{p}_i$ (which is increasing with F and T). To gain further insight, Proposition 2 relates firms' market participation decisions to their characteristics.

Proposition 2. *Given a market participation cost F, a proportional trading cost T and a market permit price $p > T$, the sets of buying and selling firms are defined by*

$$\begin{aligned}
&\mathcal{D}(p,F,T) = \{i \,|\, \alpha_i > \alpha^+(p,F,T;\beta_i) \wedge \beta_i > 0\}, \textit{ and}\\
&\mathcal{S}(p,F,T) = \big\{\{i \,|\, \alpha_i < \alpha^-(p,F,T;\beta_i) \wedge \beta_i > 0\}\\
&\qquad\qquad \cup \{i \,|\, \alpha_i < \alpha^0(p,F,T;\beta_i) \wedge -F/(p-T) < \beta_i \leq 0\} \cup \{i \,|\, \beta_i \leq -F/(p-T)\}\big\},
\end{aligned}$$

and $\mathcal{A}(p,F,T) = \mathcal{I} \setminus \{\mathcal{D}(p,F,T) \cup \mathcal{S}(p,F,T)\}$ denotes the set of autarkic firms, where

$$\begin{aligned}
\alpha^\pm(p,F,T;\beta) &= \big(F + (p \pm T)\beta \pm \sqrt{F(F + 2(p \pm T)\beta)}\big)/\beta^2 > 0,\\
\textit{and}\;\; \alpha^0(p,F,T;\beta) &= (p-T)^2/(2(F + (p-T)\beta)) > 0.
\end{aligned}$$

In particular, $\mathcal{D}$ and $\mathcal{S}$ are of decreasing measure as F or T increases and $\mathcal{D}$ (resp. $\mathcal{S}$) is of decreasing (resp. increasing) measure as p increases, ceteris paribus. Individual efficiency gains are $G_i(p+T) - F \geq 0$ (resp. $G_i(p-T) - F \geq 0$) for firm i in $\mathcal{D}$ (resp. $\mathcal{S}$).

Proof. See Appendix 2.6.3. □

Proposition 2 extends Proposition 1 in the presence of fixed and proportional trading costs. Specifically, for p large (resp. low) enough one has $\mathcal{D} = \varnothing$ (resp. $\mathcal{S} = \varnothing$); for $F = T = 0$ one has $\mathcal{A} = \varnothing$, $\mathcal{D} = \{i|\alpha_i\beta_i > p\}$ and $\mathcal{S} = \{i|\alpha_i\beta_i < p\}$; for F and T large enough one has $\mathcal{D} = \mathcal{S} = \varnothing$ and $\mathcal{A} = \mathcal{I}$. For intermediate admissible values of F and

T and a feasible price p, Figure 2.3 maps the zones where buying (red), selling (green) and autarkic (grey) firms are located in the (α, β)-space. The notions of admissible costs and feasible price are formalized in Lemma 2 below. Moreover, the blue (resp. yellow) arrows indicate how the participation frontiers move in response to an increase in F and T (resp. p).[43]

It is worthwhile describing each zone demarcated in Figure 2.3. We proceed from left to right and bottom to top:[44]

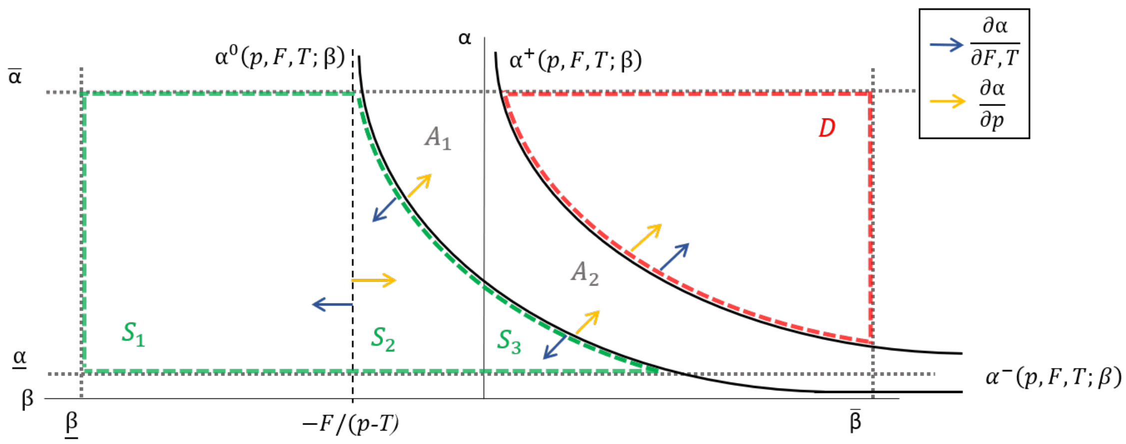
- $\mathcal{S}_1$ When $\beta_i \leq -F/(p-T)$, firm i more than recovers the fixed cost by just selling its initial surplus ($-\beta_i(p-T) \geq F$). Because this comes at no other cost for firm i, this holds whatever its marginal abatement cost α_i. Moreover, firm i finds it profitable to also abate $(p-T)/\alpha_i > 0$ and sell the corresponding amount of freed-up permits.[45]
- $\mathcal{S}_2$ When $-F/(p-T) < \beta_i \leq 0$, selling the initial surplus is not enough to cover the fixed cost. Because firm i can abate at a sufficiently low cost at the margin (i.e. $\alpha_i < \alpha^0$), it make profits by selling both surplus and freed-up permits $(p-T)/\alpha_i - \beta_i$.
- $\mathcal{A}_1$ When $-F/(p-T) < \beta_i \leq 0$, selling the initial surplus is not enough to cover the fixed cost. Because firm i cannot abate at a sufficiently low cost at the margin (i.e. $\alpha_i > \alpha^0$), it is better off under autarky, i.e. not using its surplus permits and not abating.
- $\mathcal{S}_3$ When $\beta_i > 0$ but small and abatement is sufficiently cheap at the margin (i.e. $\alpha_i < \alpha^-$) firm i abates to both meet compliance and sell some freed-up permits $(p-T)/\alpha_i - \beta_i$.
- $\mathcal{A}_2$ When $\beta_i > 0$ is relatively larger and/or abatement is relatively less cheap at the margin (i.e. $\alpha^- \leq \alpha_i \leq \alpha^+$) firm i is better off abating its deficit only so as to comply without entering the market and incurring the associated trading costs.
- $\mathcal{D}$ When $\beta_i > 0$ becomes larger and/or abatement becomes more expensive at the margin (i.e. $\alpha_i > \alpha^+$) firm i is better off incurring the trading costs so as to purchase permits to cover some portion of its deficit, the remainder being abated internally.

[43]The analytical derivations necessary to characterize these movements are collected in Appendix 2.6.3.

[44]In an intertemporal setting with banking and borrowing our categories would need be amended to reflect arbitrage opportunities, which would have a bearing on price formation and compliance costs. For instance, firms in $\mathcal{S}_1$, $\mathcal{S}_2$, $\mathcal{A}_1$ and $\mathcal{S}_3$ could bank some surplus permits for future compliance or sales (if they expect the discounted price to be higher or to sell them in larger batches to reduce trading costs) or firms in $\mathcal{A}_2$ and $\mathcal{D}$ could borrow future permits to cover a share of today's shortage and delay the full cost of compliance.

[45]With p given, one might think that firm i abates less than when $T = 0$ by T/α_i. However, because p in equilibrium hinges on the trading costs, one cannot conclude prima facie. This applies to all zones.

FIGURE 2.3: Market participation frontiers given price p and trading costs F and T



Importantly, note that with $F = 0$ and $T > 0$, the demand and supply sets in Proposition 2 rewrite $\mathcal{D} = \{i|\alpha_i > (p+T)/\beta_i \wedge \beta_i > 0\}$ and $\mathcal{S} = \{\{i|\alpha_i < (p-T)/\beta_i \wedge \beta_i > 0\} \cup \{i|\beta_i \leq 0\}\}$. That is, overallocated firms would always find it profitable to sell their extra permits at a price $p > T$ so in our model a fixed entry cost is necessary to have that some overallocated firms prefer autarky over market participation. Additionally, when $F > 0$ and both trading costs increase, the last permit supplier has characteristics $(\underline{\alpha}, \underline{\beta})$. It drops out of the market when $\alpha^0(p, F, T; \underline{\beta}) = \underline{\alpha}$. Symmetrically, on the demand side, as trading costs rise, the last buying firm has characteristics $(\bar{\alpha}, \bar{\beta})$. It switches to autarkic compliance when $\alpha^+(p, F, T; \bar{\beta}) = \bar{\alpha}$. Lemma 2 summarizes the above considerations.

Lemma 2. *The fixed and proportional trading costs F and T are said admissible when*

$$F < \bar{\alpha}\bar{\beta}^2/2 \text{ and } 2T + \sqrt{\underline{\beta}^2\underline{\alpha}^2 + 2\underline{\alpha}F} + \sqrt{2\bar{\alpha}F} < \bar{\alpha}\bar{\beta} - \underline{\alpha}\underline{\beta}. \tag{2.4}$$

When one of the above two conditions does not hold, the market breaks down. Given admissible trading costs F and T, a permit price p is said feasible when

$$\underline{\beta}\underline{\alpha} + T + \sqrt{\underline{\beta}^2\underline{\alpha}^2 + 2\underline{\alpha}F} < p < \bar{\alpha}\bar{\beta} - T - \sqrt{2\bar{\alpha}F}. \tag{2.5}$$

Proof. See Appendix 2.6.4. □

Trading costs are said admissible when positive supply and demand can emerge on the market – roughly speaking, when they are not too large. When this is not the case, the market breaks down. A permit price is said feasible when it may clear the market – it is thus necessarily bounded by the participation price thresholds of the last potential permit buyer $(\bar{\alpha}, \bar{\beta})$ and seller $(\underline{\alpha}, \underline{\beta})$ on the market as given in Lemma 1. Note that the set of feasible prices in (2.5) is not empty provided that trading costs are admissible, i.e. if they satisfy (2.4).

Equipped with Proposition 2, supply and demand functions can then be defined as follows

$$S(p,F,T) = \int_{\mathcal{S}(p,F,T)} (a_i^*(p-T) - \beta_i)\mathrm{d}i \text{ and } D(p,F,T) = \int_{\mathcal{D}(p,F,T)} (\beta_i - a_i^*(p+T))\mathrm{d}i,$$

where $a_i^*(x) = x/\alpha_i$ is participating firm i's optimal abatement decision given the net permit price $x = p \pm T$. If we denote by h the density function of the β_i's and by $g(\cdot|\beta)$ that of the α_i's conditional on the β_i's, supply and demand rewrite

$$\begin{aligned} S(p,F,T) = &\int_{\underline{\beta}}^{-F/(p-T)} \int_{\underline{\alpha}}^{\bar{\alpha}} ((p-T)/x - y)g(x|y)h(y)\mathrm{d}x\mathrm{d}y \\ &+ \int_{-F/(p-T)}^{0} \int_{\underline{\alpha}}^{\alpha^0(p,F,T;y)} ((p-T)/x - y)g(x|y)h(y)\mathrm{d}x\mathrm{d}y \\ &+ \int_{0}^{\bar{\beta}} \int_{\underline{\alpha}}^{\alpha^-(p,F,T;y)} ((p-T)/x - y)g(x|y)h(y)\mathrm{d}x\mathrm{d}y, \end{aligned} \tag{2.6}$$

$$\text{and } D(p,F,T) = \int_{0}^{\bar{\beta}} \int_{\alpha^+(p,F,T;y)}^{\bar{\alpha}} (y - (p+T)/x)g(x|y)h(y)\mathrm{d}x\mathrm{d}y, \tag{2.7}$$

Lemma 3 characterizes how S and D vary with F, T and p alternatively.

Lemma 3. *For any admissible trading costs F and T and feasible market price p, it holds that*

$$\frac{\partial S}{\partial p} > 0, \ \frac{\partial S}{\partial F} < 0, \ \frac{\partial S}{\partial T} < 0, \ \frac{\partial D}{\partial p} < 0, \ \frac{\partial D}{\partial F} < 0, \ \textit{and} \ \frac{\partial D}{\partial T} < 0.$$

Proof. See Appendix 2.6.5. □

Equipped with Lemmas 2 and 3 and letting $V = S - D$ denote the net permit supply function, we can now state the following result.

Proposition 3. *Given admissible trading costs F and T, there exists a unique feasible permit price $\hat{p}$ that clears the market, i.e. $V(\hat{p},F,T) = 0$.*

Proof. See Appendix 2.6.6. □

Proposition 3 ensures the existence and uniqueness of a market equilibrium in the presence of admissible fixed and proportional trading costs. Except with zero costs where the equilibrium collapses to the frictionless one, i.e. $V(p^\star,0,0) = 0$, it is otherwise apparent from (2.6) and (2.7) that $\hat{p}$ does not admit a simple closed-form solution in general. Below we thus seek to derive some properties of the equilibrium in the presence of trading costs using comparative statics.

2.3.3 Equilibrium with trading costs: Some properties

In this section, we leverage the equilibrium framework developed in Section 2.3.2 to extend the comparative static results in Stavins, 1995 and Montero, 1998. Specifically, we analyze the sensitivity of market equilibrium outcomes to incremental changes in the trading costs and firms' permit allocations. We complement our formal analysis with analytical and numerical examples to go beyond the impacts of incremental changes and gain further insight.

2.3.3.1 Impacts of a change in trading costs

Consider an arbitrarily small increase $\mathrm{d}K > 0$ in the trading cost $K = F$ or T. By virtue of the implicit function theorem, the resulting price response $\mathrm{d}\hat{p}$ in the vicinity of the equilibrium reads

$$\frac{\mathrm{d}\hat{p}}{\mathrm{d}K} = -\frac{\partial V(\hat{p}, F, T)/\partial K}{\partial V(\hat{p}, F, T)/\partial p} \gtrless 0, \tag{2.8}$$

which cannot unambiguously be signed in general. Indeed, Lemma 3 shows that $\partial V/\partial p > 0$ but the sign of $\partial V/\partial K$ is indefinite and hinges on the relative magnitudes of the demand and supply responses to the trading cost increase.[46] For instance, when demand is more responsive than supply, i.e. $|\partial D/\partial K| > |\partial S/\partial K|$, then $\mathrm{d}\hat{p}/\mathrm{d}K < 0$. In words, the equilibrium price is lowered as demand is relatively more constricted than supply, and vice versa. As a corollary, it follows that

$$\hat{p} \gtrless p^{\star}, \tag{2.9}$$

depending on the distributions of the firms' characteristics α_i and β_i and the levels of the trading costs. This showcases the break-down of the Coasean independence property in the presence of trading costs – in particular, equilibrium outcomes hinge on the initial allocation of permits across firms. Further taking the total differentials of supply and demand yields

$$\frac{\mathrm{d}S}{\mathrm{d}K} = \underbrace{\frac{\partial S}{\partial K}}_{<0} + \underbrace{\frac{\partial S}{\partial p}}_{>0}\underbrace{\frac{\mathrm{d}\hat{p}}{\mathrm{d}K}}_{\gtrless 0} \quad \text{and} \quad \frac{\mathrm{d}D}{\mathrm{d}K} = \underbrace{\frac{\partial D}{\partial K}}_{<0} + \underbrace{\frac{\partial D}{\partial p}}_{<0}\underbrace{\frac{\mathrm{d}\hat{p}}{\mathrm{d}K}}_{\gtrless 0}, \tag{2.10}$$

[46] Note that even taking (2.8) in the small as F and/or $T \to 0$ also yields an indefinite sign.

which, on the face of it, cannot unambiguously be signed either. Yet, $\mathrm{d}S/\mathrm{d}K = \mathrm{d}D/\mathrm{d}K$ must hold in equilibrium,[47] which in conjunction with (2.10) implies that $\mathrm{d}S/\mathrm{d}K = \mathrm{d}D/\mathrm{d}K < 0$. In words, an increase in the trading costs always lowers the equilibrium volume of trade.

As a result, the total regulatory control costs, i.e. the costs of abatement and trading summed over all firms, always increase as K rises. Because firms choose whether to trade or not, and if so the extent thereof, by minimizing their compliance costs, there exists a decreasing mapping between the total volume of trade (which measures the degree of cost-effective reallocation of abatement among firms) and the total control costs. In words, therefore, an increase in the trading costs negatively impacts welfare by consuming more monetary resources and stifling more trades which would have otherwise been mutually beneficial, at both the extensive and intensive margins. Proposition 4 summarizes the above results.

Proposition 4. *In response to an increase in the fixed or proportional trading cost, the equilibrium volume of trade (resp. total regulatory control costs) always decreases (resp. increases) and vice versa. However, the market equilibrium price may increase or decrease.*

Proof. See above. □

To illuminate our general results, we exclusively focus on the equilibrium price impacts of a shift in the trading costs for two reasons. First, because Stavins, 1995 and Montero, 1998 shut down this channel in their comparative static analyses of trading costs. Second, because price impacts can go both ways, it is worthwhile investigating their determinants per se.

To go beyond the equilibrium sensitivity to incremental changes in the trading costs characterized in Proposition 4, below we provide both analytical and numerical illustrations. First, we consider two simple analytical examples for the distributions of the firms' characteristics whereby we are able to derive implicit closed-form solutions for the equilibrium price which lend themselves to economic interpretation. Second, we develop three numerical examples in more general cases to gain further insight into the price impacts of trading costs.

Analytical examples. We primarily focus on the price impacts of the fixed trading cost, i.e. we let $F \geq 0$ and $T = 0$. We also let firms be homogeneous in terms of initial net deficit, i.e. $\beta_i = \beta = \mathcal{U} - \mathcal{Q} > 0$ for all i in $\mathcal{I}$, and proceed with two alternative

[47] One can formally see this by unpacking (2.8) with $V = S - D$ and term identification with (2.10).

distributions of the α_i's, namely

$$g_1(x) = 2x/(\bar{\alpha}^2 - \alpha^2) \text{ and } g_2(x) = \bar{\alpha}\alpha/(x^2(\bar{\alpha} - \alpha)),$$

for $x \in [\bar{\alpha}; \alpha]$ and $g_{1,2}(x) = 0$ elsewhere. These density functions are normalized to a unitary mass and cherry-picked to ensure both analytical tractability and clear-cut results which are otherwise hard to come by.[48] They represent two opposite distributions of the α_i's: with g_1 (resp. g_2), $\{\alpha_i\}_i$ is skewed towards high (resp. low) values. The sketches of the derivations leading to the following results are gathered in Appendix 2.6.7.

Case 1. Fix $\beta_i = \beta > 0$ for all i in $\mathcal{I}$ and let $g = g_1$. Then $\hat{p}_1$ is implicitly defined by

$$\hat{p}_1 + \frac{2F\sqrt{F(F + 2\beta\hat{p}_1)}}{\beta^3(\bar{\alpha} - \alpha)} = p_1^\star, \tag{2.11}$$

where $p_1^\star = \beta(\bar{\alpha} + \alpha)/2$. In this case, $\hat{p}_1 \leq p_1^\star$ with equality in $F = 0$ and $\mathrm{d}\hat{p}_1/\mathrm{d}F < 0$.

Case 2. Fix $\beta_i = \beta > 0$ for all i in $\mathcal{I}$ and let $g = g_2$. Then $\hat{p}_2$ is implicitly defined by

$$\hat{p}_2 - \frac{4F\bar{\alpha}^2\alpha^2}{(\bar{\alpha}^2 - \alpha^2)\hat{p}_2^3}\sqrt{F(F + 2\beta\hat{p}_2)} = p_2^\star, \tag{2.12}$$

where $p_2^\star = 2\beta\bar{\alpha}\alpha/(\bar{\alpha} + \alpha)$. In this case, $\hat{p}_2 \geq p_2^\star$ with equality in $F = 0$ and $\mathrm{d}\hat{p}_2/\mathrm{d}F > 0$.

Observe that $p_1^\star > p_2^\star$. Indeed, with a homogeneous deficit β across firms the frictionless price is higher the more skewed the distribution of the α_i's towards high values. Crucially, a fixed trading cost tends to mitigate this. When the α_i's are tilted towards high values, introducing or increasing the fixed cost tends to evict more firms with a high α_i (i.e. demanders) than with a low α_i (i.e. suppliers), ceteris paribus. This entails that demand is more constricted than supply, hence a downward pressure on the price. The converse holds when the α_i's are skewed towards low values as a higher fixed cost shrinks supply more than demand, ceteris paribus. Hence, a fixed trading cost tends to have a tempering effect on the price when the frictionless price is 'high' – and conversely, it tends to hike $\hat{p}$ when $p^\star$ is 'low'.

Numerical examples. To expand the parameter space and enrich the analysis, we let $\{\alpha_i\}_i$ and $\{\beta_i\}_i$ follow independent beta distributions $B(\alpha_\alpha, \beta_\alpha)$ and $B(\alpha_\beta, \beta_\beta)$ and consider both fixed and proportional trading costs simultaneously. We set $\underline{\alpha} = 1$, $\bar{\alpha} = 10$, $\underline{\beta} = -5$ and $\bar{\beta} = 10$ and consider three cases: both $\{\alpha_i\}_i$ and $\{\beta_i\}_i$ uniform (i.e. $\alpha_\alpha =$

[48] For instance, when $\{\alpha_i\}_i$ is uniformly distributed we arrive at an analytically intractable transcendental equation in $\hat{p}$. The ordering between $\hat{p}$ and $p^\star$ thus depends on F in a non-straightforward way.

$\alpha_\beta = \beta_\alpha = \beta_\beta = 1$); $\{\alpha_i\}_i$ skewed towards high values (i.e. $\alpha_\alpha = 3$, $\beta_\alpha = 1$) with $\{\beta_i\}_i$ uniform; and $\{\beta_i\}_i$ skewed towards high values (i.e. $\alpha_\beta = 3$, $\beta_\beta = 1$) with $\{\alpha_i\}_i$ uniform.[49]

Given the trading costs F and T we can solve numerically for $\hat{p}_0$ such that $V(\hat{p}_0, F, T) = 0$, jointly verifying the cost admissibility conditions. Specifically, we seek $\hat{p}_0 = \min p$ such that $D - S > 0$ and $\hat{p}_0$ is feasible. The left column in Figure 2.4 depicts our results and shows the ratios $\hat{p}_0/p_0^\star$ in the (F, T)-space in the three cases, with $V(p_0^\star, 0, 0) = 0$. The thick black line delineates the admissible cost range defined by (2.4), i.e. the market breaks down above it.

With $\{\alpha_i\}_i$ and $\{\beta_i\}_i$ both uniform (Figure 2.4a) the market price in the presence of trading costs is always larger than absent trading costs ($\hat{p}_0/p_0^\star \geq 1$) and it gets larger the larger F or T (contour lines are downward-sloping) but increases relatively more with T than F (contour lines are convex). For instance, $\hat{p}_0$ can be five times as large as $p_0^\star$ when $F = 0$ and T is large while it is at most twice as large when $T = 0$ and F is large. This is no longer so in the other two cases: $\hat{p}_0$ can be lower than $p_0^\star$ for some trading costs (e.g. when F is large and T small in Figure 2.4e) and is non-monotonic in the trading costs (i.e. contour lines have distorted U shapes in Figures 2.4c and 2.4e). In particular, $\hat{p}_0$ increases with the trading costs when they are 'low enough' but the converse holds when they are 'large enough'.

Generally speaking, we find that the higher the frictionless price to start with, the relatively lower the market price in the presence of trading costs. Moreover, only when the frictionless price is sufficiently high can trading costs lead to a lower price level for some cost pairs. This relates to the aforementioned tempering price effect of trading costs.

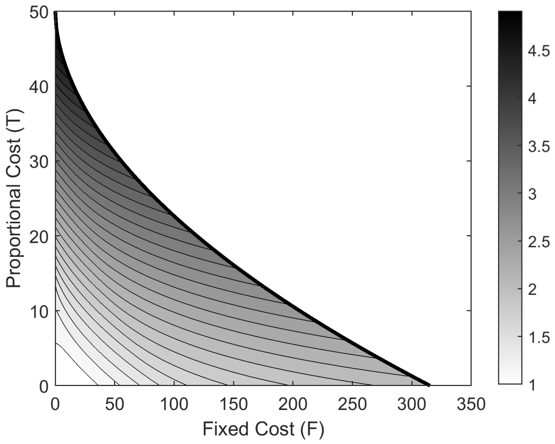
2.3.3.2 Impacts of a change in total supply and individual allocations

We now study the equilibrium price impacts of a shift in total supply and firm-level allocations in the presence of constant trading costs. We refer the reader to Stavins, 1995 and Montero, 1998 for illustrations of how the total volume of trade and compliance costs vary with firms' initial allocations. Compared to these comparative static analyses taking the perspective of a given firm (i.e. assuming the market price is invariant), we use our equilibrium framework to analyze the case where all firms' allocations can vary simultaneously, which affects both the market price and firms' trading decisions. This in turn leads to different results. Contrary to Stavins, 1995 for instance, the way permits

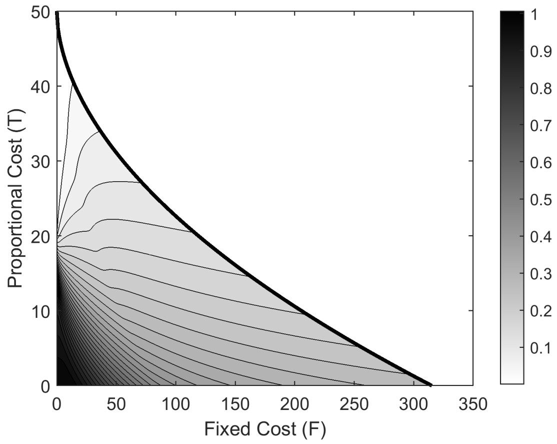
[49]The cases where $\{\alpha_i\}_i$ or $\{\beta_i\}_i$ are skewed towards low values lead to magnified but qualitatively similar results as for the case of $\{\alpha_i\}_i$ and $\{\beta_i\}_i$ both uniform, hence omitted here.

FIGURE 2.4: Ratios $\hat{p}_0 / p_0^\star$ (left) and $\frac{\hat{p}_t - \hat{p}_0}{\hat{p}_0} \big/ \frac{p_t^\star - p_0^\star}{p_0^\star}$ (right)

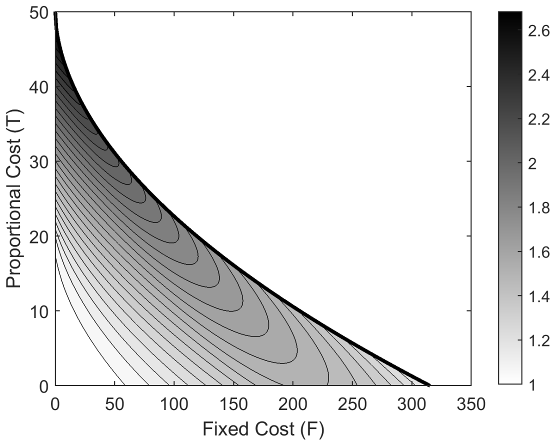
(A) $\alpha_\alpha = \beta_\alpha = \alpha_\beta = \beta_\beta = 1$ $(p_0^\star = 9.8)$



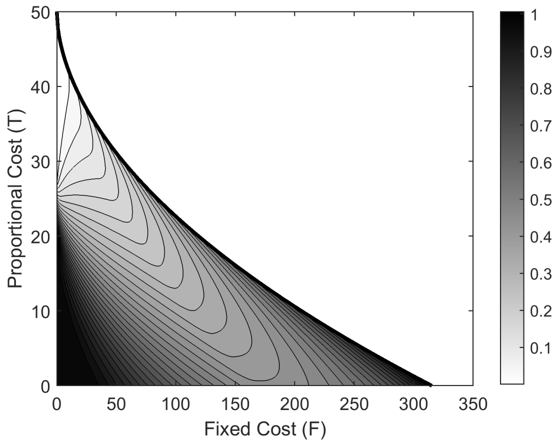
(B) $\alpha_\alpha = \beta_\alpha = \alpha_\beta = \beta_\beta = 1$ $(p_t^\star = 13.7)$



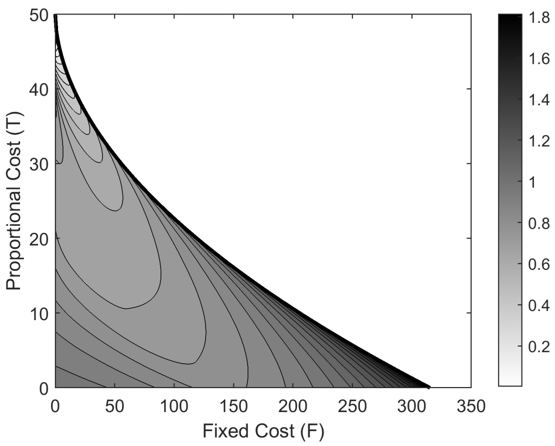
(C) $\alpha_\alpha = 3, \beta_\alpha = \alpha_\beta = \beta_\beta = 1$ $(p_0^\star = 18.0)$



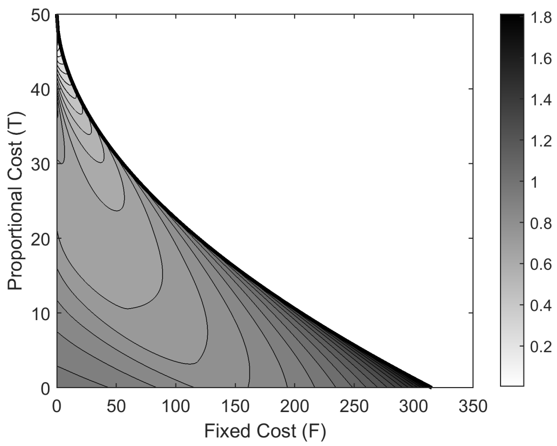
(D) $\alpha_\alpha = 3, \beta_\alpha = \alpha_\beta = \beta_\beta = 1$ $(p_t^\star = 25.2)$



(E) $\alpha_\beta = 3, \alpha_\alpha = \beta_\alpha = \beta_\beta = 1$ $(p_0^\star = 24.4)$



(F) $\alpha_\beta = 3, \alpha_\alpha = \beta_\alpha = \beta_\beta = 1$ $(p_t^\star = 28.3)$



Note: The subscript 0 (resp. t) indicates the pre (resp. post) supply tightening situation.

are allocated among firms does affect equilibrium outcomes even with linear marginal trading costs.

We consider an arbitrarily small variation in $\{\beta_i\}_i$, i.e. we let β_i change to $\beta_i + \mathrm{d}\beta_i$ for all i in $\mathcal{I}$, possibly with $\mathrm{d}\beta_i \neq \mathrm{d}\beta_j$, and then let the price adapt to $\hat{p} + \mathrm{d}\hat{p}$ so that $V(\hat{p} + \mathrm{d}\hat{p}, F, T) = 0$ remains satisfied. This is tantamount to taking the total differential of $V(\hat{p}, F, T) = 0$ w.r.t. $\hat{p}$ and all β_i's. With a slight abuse of notation for the partial derivatives w.r.t. the β_i's, one has

$$\frac{\partial V(\hat{p}, F, T)}{\partial p}\mathrm{d}\hat{p} + \int_{\mathcal{I}} \frac{\partial V(\hat{p}, F, T)}{\partial \beta_i}\mathrm{d}\beta_i \mathrm{d}i = 0. \tag{2.13}$$

For the sake of the argument, we here only consider induced changes at the intensive margin (i.e. within $\mathcal{S}$ and $\mathcal{D}$ as given prior to the change in $\{\beta_i\}_i$) and ignore those at the extensive margin (i.e. changes due to the shifts in the locations of the participation frontiers in Figure 2.3). Extensive margin impacts, which render the exposition more complex but do not change the nature of the results, are formally treated and discussed in Appendix 2.6.8.

Noting that $\dfrac{\partial V}{\partial \beta_i} = -\displaystyle\int_{\mathcal{S}(\hat{p},F,T)\cup\mathcal{D}(\hat{p},F,T)} \delta(j = i)\mathrm{d}j$ where $\delta(\cdot)$ denotes the Dirac distribution, (2.13) simplifies to

$$\frac{\partial V(\hat{p}, F, T)}{\partial p}\mathrm{d}\hat{p} = \int_{\mathcal{S}(\hat{p},F,T)\cup\mathcal{D}(\hat{p},F,T)} \mathrm{d}\beta_i \mathrm{d}i, \tag{2.14}$$

meaning that the sign and magnitude of $\mathrm{d}\hat{p}$ hinge upon the overall net change in the β_i's over $\mathcal{S}(\hat{p}, F, T) \cup \mathcal{D}(\hat{p}, F, T)$. This is because allocation changes for autarkic firms have no market impacts given our exclusive focus on the intensive margin impacts. Interestingly, note that the mere reshuffling of individual allocations, while keeping total supply invariant, may also influence the price outcome as the $\mathrm{d}\beta_i$'s may not cancel out over $\mathcal{S}(\hat{p}, F, T) \cup \mathcal{D}(\hat{p}, F, T)$.

Now consider that total supply is tightened by $\mathrm{d}\mathcal{Q} > 0$ and that the tightening is uniformly distributed among all firms.[50] Because $\mathcal{I}$ is of mass one, we have that $\mathrm{d}\beta_i = \mathrm{d}\mathcal{Q}$ for all i. If we let $|\cdot|$ denote the mass (or measure) of a set, (2.14) then rewrites

$$\frac{\mathrm{d}\hat{p}}{\mathrm{d}\mathcal{Q}} = \frac{|\mathcal{S}(\hat{p}, F, T)| + |\mathcal{D}(\hat{p}, F, T)|}{\partial V(\hat{p}, F, T)/\partial p} > 0, \tag{2.15}$$

that is, the price response to the tightening is always positive in the presence of trading costs. But how does its magnitude compare to that in the frictionless case? Without

[50] Two alternative firm-level distributions of the tightening are considered in Appendix 2.6.8.

trading costs, (2.14) reads

$$\frac{\partial V(p^\star,0,0)}{\partial p}\mathrm{d}p^\star = \int_{\mathcal{I}} \mathrm{d}\beta_i \mathrm{d}i = \mathrm{d}\mathcal{Q}, \tag{2.16}$$

so that

$$\frac{\mathrm{d}\hat{p}/\mathrm{d}\mathcal{Q}}{\mathrm{d}p^\star/\mathrm{d}\mathcal{Q}} = \underbrace{\big(|\mathcal{S}(\hat{p},F,T)| + |\mathcal{D}(\hat{p},F,T)|\big)}_{\text{distribution effect } \leq 1} \underbrace{\frac{\partial V(p^\star,0,0)/\partial p}{\partial V(\hat{p},F,T)/\partial p}}_{\text{price effect } \geq 1} \gtrless 1. \tag{2.17}$$

The ordering of $\mathrm{d}\hat{p}$ and $\mathrm{d}p^\star$ is ambiguous in general and hinges on two countervailing forces. First, the overall impact on the net demand for permits (holding the price constant) relative to that without trading costs which ultimately depends on how the tightening is distributed among firms. In the intensive margin only case, for a given incidence of the tightening, this *distribution effect* always works to mitigate the price increase, all the more so that trading costs are large and the mass of autarkic firms is sizable. Second, the ratios of the sensitivities of the net supply functions to a price change with and without trading costs. In the intensive margin only case, this *price effect* always works to magnify the price increase, all the more so that trading costs are large.[51] This yields the overall ambiguous effect in (2.17).

We now state the following result in the general case of any change in supply inclusive of the induced impacts at both the intensive and extensive margins.

Proposition 5. *The market price response to a supply change can be amplified or dampened in the presence of trading costs relative to frictionless conditions. This hinges on a distribution effect (the relative impact on net permit demand holding the price constant) and a price effect (the relative price elasticity of net permit demand) which are generally countervailing.*

Proof. See Appendix 2.6.8. □

In the general case the distribution and price effects can be greater or lower than one. Specifically, the distribution (resp. price) effect is likely to be predominantly lower (resp. greater) than one, except possibly when trading costs are small. In particular, when $F = 0$, the extensive margin effects are nil so that this case collapses to the above analysis. Appendix 2.6.8 also discusses how the magnitude of the distribution effect depends on the type of firm-level incidence of the supply change. We now turn to analytical and numerical examples.

[51] Since $|\mathcal{S}| + |\mathcal{D}| \leq |\mathcal{I}| = 1$, *distribution effect* ≤1 and decreases as $|\mathcal{A}|$ increases. $\partial V(p^\star,0,0)/\partial p = \int_{\mathcal{I}} \mathrm{d}i/\alpha_i$ while $\partial V(\hat{p},F,T)/\partial p = \int_{\mathcal{S}\cup\mathcal{D}} \mathrm{d}i/\alpha_i$ so *price effect* ≥1. See Appendix 2.6.8 for more details.

Analytical examples (cont'd). We consider that pursuant to some regulatory amendment overall supply $\mathcal{Q}$ is reduced by an arbitrarily small amount $\mathrm{d}\mathcal{Q} > 0$, which translates into a small increase $\mathrm{d}\beta = \mathrm{d}\mathcal{Q}$ in the firms' uniform deficit. We have the following results.

Case 1. The market price response to a small uniform supply tightening of $\mathrm{d}\beta$ is positive, i.e. $\mathrm{d}\hat{p}_1/\mathrm{d}\beta > 0$. However, only when $\hat{p}_1$ is not too small does it hold that $\mathrm{d}\hat{p}_1/\mathrm{d}\beta \geq \mathrm{d}p_1^\star/\mathrm{d}\beta > 0$, specifically when $(p_1^\star - 3F/\beta)/5 \leq \hat{p}_1 \leq p_1^\star$.

Case 2. The market price response to a small uniform supply tightening of $\mathrm{d}\beta$ is positive, i.e. $\mathrm{d}\hat{p}_2/\mathrm{d}\beta > 0$. However, only when $\hat{p}_2$ is not too large does it hold that $\mathrm{d}\hat{p}_2/\mathrm{d}\beta \geq \mathrm{d}p_2^\star/\mathrm{d}\beta > 0$, specifically when $p_2^\star \leq \hat{p}_2 \leq p_2^\star + \sqrt{p_2^\star(p_2^\star + 3F/(2\beta))}$.

Intuitively, tightening supply always implies higher price levels in the presence of a fixed cost, but the price rise can be magnified or dampened relative to frictionless conditions. The two cases suggest that the price response is more likely to be magnified in the presence of a fixed cost when $\hat{p}$ is not too distant from $p^\star$ prior to the tightening, ceteris paribus. We investigate this further with numerical examples.

Numerical examples (cont'd). We illustrate a uniform supply tightening with a shift in the support of the distribution $\{\beta_i\}_i$ from $[-5; 10]$ (indexed by 0) to $[-4; 11]$ (indexed by t). The right column in Figure 2.4 depicts our results and shows the ratios of the relative induced price increase $\frac{\hat{p}_t - \hat{p}_0}{\hat{p}_0}$ with trading costs to the relative induced price increase under frictionless conditions $\frac{p_t^\star - p_0^\star}{p_0^\star}$ in the (F, T)-space in the three cases considered.

We find that the relative induced price increase in the presence of trading costs is less pronounced the larger $\hat{p}_0$ relative to $p_0^\star$ to start with. Consequently, it tends to be larger under frictionless conditions than present trading costs most of the time in our simulations. Only in one case do we find that the relative price increase is larger with trading costs than without, namely in Figure 2.4f when F is large and $\hat{p}_0$ is close to or lower than $p_0^\star$.

2.4 Illustration

In this section, we illustrate our theoretical results based on actual market data. Specifically, we consider the universe of allocations, emissions, transactions and prices in Phase II of the EU ETS (2008-2012) to discipline both the calibration of model parameters and selection of practically relevant values for the fixed and proportional trading costs. We next leverage our calibrated model to compare the relative implications of various supply-tightening policies in terms of market price responses and compliance costs, with and without trading costs.

2.4.1 Calibration to EU ETS Phase II

We utilize our transaction and compliance databases consolidated at the firm level to calibrate the model parameters for each year in Phase II. We proceed in two steps. First, we infer yearly firms' characteristics $(\alpha_{i,t}, \beta_{i,t})$ conditional on given pairs of trading costs (F, T). Second, we select the trading cost pair that best rationalizes firms' observed participation in trading and, where applicable, the sign of their net market positions.

2.4.1.1 Inferring firms' characteristics with given trading costs

Yearly initial allocations and verified emissions are readily available at the polluting unit (or account) level from the EUTL which we consolidate at the firm level (see Appendix 2.7 for the methodology). We respectively denote them $q^r_{i,t}$ and $e^r_{i,t}$ for firm i in year t. We also compute yearly-averaged EUA spot prices p^r_t using ICE data. Except for the consolidation procedure, this is quite straightforward. We now need to make assumptions to set firms' yearly baseline emissions and marginal abatement cost slopes (which are both unobservable quantities) and control for banking and borrowing in our static setting. In a context where relevant quantities are either scarce or hard to reconstruct ex post, we opt for workable assumptions allowing for a first-pass yet reasonable model calibration.

We set year-t baseline emissions $u_{i,t}$ as the moving averages of i's verified emissions over the three preceding years $t-3$ to $t-1$. This captures the persistence in emissions demand over time and a steadily declining aggregate trend (e.g. Quemin and Trotignon, 2019a). This proxy is further adjusted with yearly-fixed effects η_t introduced below. We exclude firms with implied negative abatement, i.e. with $u_{i,t} - e^r_{i,t} < 0$, which is the case for 30% of the firms on average across years. This leads to some changes in the size of the annual samples of firms.

Next, we set firms' marginal abatement cost slopes based on the equimarginal value principle applied to the total permit cost (i.e. permit price adjusted for the proportional trading cost) using observed prices p^r_t and implied abatement levels $u_{i,t} - e^r_{i,t}$. The imputed $\alpha_{i,t}$'s thus need to be conditioned on observed market participation decisions and net positions, that is

$$\alpha_{i,t} = \begin{cases} (p^r_t + T)/(u_{i,t} - e^r_{i,t}) & \text{if} \quad i \in \mathcal{D}^r_t \\ (p^r_t - T)/(u_{i,t} - e^r_{i,t}) & \text{if} \quad i \in \mathcal{S}^r_t \\ p^r_t/(u_{i,t} - e^r_{i,t}) & \text{if} \quad i \in \mathcal{A}^r_t \end{cases} \tag{2.18}$$

where $\mathcal{D}_t^r$, $\mathcal{S}_t^r$ and $\mathcal{A}_t^r$ are the sets of observed net buying, net selling and autarkic firms in year t, respectively. In (2.18) we assume that autarkic firms treat the permit price as a relevant signal to guide their abatement decisions though they do not effectively trade.

We then adjust firms' allocations for the temporal dimension that our static model does not capture, i.e. we compute effective allocation levels net of temporal intra-firm redistribution.[52] To that end, we begin by imputing firms' permit bank dynamics as

$$b_{i,t}^r = b_{i,t-1}^r + q_{i,t}^r + x_{i,t}^r - e_{i,t}^r, \tag{2.19}$$

where $b_{i,t}^r$ is firm i's observed bank carried over from year t to year $t+1$ with $b_{i,2007}^r = 0$, and $x_{i,t}^r$ is firm i's observed net permit purchase in year t. Then the banking-adjusted allocation for firm i in year t, denoted by $q_{i,t}^a$, is set as

$$q_{i,t}^a = \begin{cases} q_{i,t}^r - (b_{i,t}^r - b_{i,t-1}^r) = e_{i,t}^r - x_{i,t}^r & \text{if} \quad i \in \mathcal{D}_t^r \cup \mathcal{S}_t^r \\ q_{i,t}^r - \frac{1}{2}(b_{i,t}^r - b_{i,t-1}^r) = \frac{1}{2}(q_{i,t}^r + e_{i,t}^r) & \text{if} \quad i \in \mathcal{A}_t^r \end{cases} \tag{2.20}$$

For observed trading firms, effective allocations are simply raw allocations net of yearly bank increments $b_{i,t}^r - b_{i,t-1}^r$. That is, observed buying (resp. selling) firms are ex-ante short (resp. long) by their ex-post net traded volumes. For observed autarkic firms, we add a $\frac{1}{2}$ factor in front of the bank increment. Were it not for this factor, these firms would by construction have no need to trade ex ante as $q_{i,t}^a$ would coincide with $e_{i,t}^r$ since $x_{i,t}^r = 0$. But because one of our aims is to recover autarkic compliance via the introduction of trading costs, this arbitrary factor leaves some trading opportunities open for these firms – here selling (or buying) up to half of their yearly permit surpluses (or deficits). Indeed, as discussed in Section 2.1.1, autarkic firms could in principle increase profits by trading on the market to some extent rather than exclusively exploiting the temporal flexibility margin.[53] From (2.20) we finally compute annual permit deficits as $\beta_{i,t} = u_{i,t} - q_{i,t}^a$ and Table 2.8.1 contains some descriptive statistics on the inferred firms' characteristics $\{\alpha_{i,t}, \beta_{i,t}\}_{i,t}$ binned by sectors.

So equipped, we can populate the sets $\mathcal{D}_t$, $\mathcal{S}_t$ and $\mathcal{A}_t$ defined in Proposition 2 for any feasible price p and admissible trading costs (F, T). We consider a mesh where F and T respectively range from 0 to 200 k€ and 0 to 1.5 €/tCO_2 with steps of 1 k€ and 0.05

[52]This implies that (1) trading costs only affect the extent of annual inter-firm trading in isolation of other years and (2) each year temporal intra-firm trading is carried out before spatial inter-firm trading.

[53]The $\frac{1}{2}$ factor is arbitrary and reflects a lack of relevant empirical guidance. It affects our selected values for the trading costs thus: given the market-wide bank build-up in Phase II, a higher factor would imply less surplus permits available, hence lower trading costs to rationalize autarkic compliance, and vice versa.

€/tCO_2, and p can vary freely within the feasibility region as per (2.5). This defines supply S_t and demand D_t as per (2.6-2.7) for any discretized pair (F, T). For any given pair, we can then solve for the year-t equilibrium price $\hat{p}_t$, namely $\hat{p}_t = \min p$ subject to $D_t - S_t > 0$.

2.4.1.2 Selecting relevant trading costs

As Carlson et al. (2000, p. 1319) observe, the failure of firms to realize cost savings through trading cannot be inferred simply by comparing price levels obtained under different modeling scenarios with those that actually prevailed. Specifically in our case, a multiplicity of trading cost pairs can replicate the observed price levels p_t^r. Additionally, price formation is influenced by a variety of other factors our model does not explicitly account for. As such, the ability to replicate observed prices is not robust enough a criterion to discriminate between cost pairs. Accordingly, we eliminate the initial difference between p_t^r and the $\hat{p}_t$'s for all pairs.[54]

To this end we introduce additive yearly fixed effects η_t adjusting firms' marginal abatement cost schedules to $\alpha_{i,t}(u_{i,t} - e_{i,t}) + \eta_t$, de facto shifting firms' initial permit deficits by $\eta_t / \alpha_{i,t}$. For instance, the η_t's can be thought of as partly controlling for common shocks to or trends in firms' baseline emissions, or for firms' intertemporal trading decisions, thereby improving on our first-pass proxies for baselines and banking-adjusted allocations. Specifically, $\eta_t > 0$ corrects for higher baselines or market-wide incentives to bank or both. We then pick the η_t that eliminates the initial price wedge: for every cost pair (F, T) and year t there corresponds a unique η_t ensuring that $\hat{p}_t = p_t^r$ (if initially $\hat{p}_t < p_t^r$ then $\eta_t > 0$ and vice versa).

To make an educated guess about practically relevant trading costs values and discriminate between cost pairs, we propose to discipline the selection of trading costs by jointly minimizing the total number of modeling sorting errors and their dispersion across error types. That is, this selection criterion minimizes discrepancies between firms' participation in trading and their net market positions as predicted by the model vs. as observed in the data.

Among the six error types listed in Table 2.1, types 1-4 relate to the firms' market participation decisions while types 5-6 relate to their net market positions conditional on participation. For example, the set $\mathcal{E}_1$ (resp. $\mathcal{E}_5$) contains observed buyers (resp. sellers) mistakenly sorted as autarkic (resp. buyers) by the model given a triplet (F, T, η_t). When $F = T = 0$, no firm chooses autarky in the model so that $\mathcal{E}_1 = \mathcal{E}_2 = \varnothing$. As F and/or T

[54] This implies that we ignore the direct impacts that trading costs may have on price formation when we select a cost pair but we do capture their indirect impacts i.e. as firms adjust their participation in, and their extent of, trading based on the cost levels.

TABLE 2.1: Typology of sorting errors

Model		Observations: Autarkic	Buyer	Seller
	Autarkic	–	$\mathcal{E}_1$	$\mathcal{E}_2$
	Buyer	$\mathcal{E}_3$	–	$\mathcal{E}_5$
	Seller	$\mathcal{E}_4$	$\mathcal{E}_6$	–

rises and the autarkic zone in Figure 2.3 widens the cardinalities of these sets, $|\mathcal{E}_1|$ and $|\mathcal{E}_2|$, increase while both $|\mathcal{E}_3|$ and $|\mathcal{E}_4|$ decrease, indicating a trade-off in the cost levels. Recall that $F > 0$ is necessary to explain that some overallocated firms may remain autarkic, which causes $|\mathcal{E}_4|$ to shrink. We note that $|\mathcal{E}_5|$ and $|\mathcal{E}_6|$ are negligible relative to the numbers of participation-related errors.[55] This was to be expected because we set trading firms' effective allocations in line with their observed net market positions by construction in (2.20).

Formally, our twin objective is to (1) minimize the total number of sorting errors and (2) favor balanced distributions of these errors among error types. Goal (2) is congruent with maximizing Shannon's entropy applied to the distribution of error types $\{|\mathcal{E}_1|, \ldots, |\mathcal{E}_6|\}$. Specifically, letting $\mathcal{P}_i = |\mathcal{E}_i| / \sum_{j=1}^{6} |\mathcal{E}_j|$ denote the proportion of type-i errors, Shannon's entropy $\mathcal{H}$ is defined by

$$\mathcal{H} = -\sum_{i=1}^{6} \mathcal{P}_i \log(\mathcal{P}_i) \in [0; \log(6)],$$

and is maximal when the errors are evenly distributed, i.e. $\mathcal{P}_i = \mathcal{P}_j$ for all $i \neq j$. With N the total number of firms in the sample, we thus select (F, T) to maximize the normalized index

$$\big(\mathcal{H} / \log(6)\big) \times \big(1 - \sum_{i=1}^{6} |\mathcal{E}_i| / N\big) \in [0; 1].$$

Given the aforementioned trade-off in trading cost levels and as detailed further in Appendix 2.8, the normalized index is mostly determined by its entropy component which is inverted U shaped, hence globally concave. Our calibration results are reported in Table 2.2. In 2009, 2011 and 2012, η is close to zero, suggesting that baselines and effective allocations are on average satisfactorily parametrized for these years. In 2010, however, η is significantly larger, implying that an upward shift in the firms' initial deficits is necessary to reproduce observed prices. This can be explained by the economic downturn which dramatically decreased emissions in the three preceding years and thus our proxy for 2010 baselines.

[55] Specifically, it suffices that F or T be positive but small for $|\mathcal{E}_5|$ and $|\mathcal{E}_6|$ to become nil.

TABLE 2.2: Annual calibration results (2008-2012)

	p_t^r	η_t	F	T	T/p_t^r	$\mathcal{H}/\log(6)$	$1-\sum_{i=1}^{6}\lvert\mathcal{E}_i\rvert/N$
2008	19.6	4.1	10	0.55	2.8%	0.74	0.90
2009	13.3	-0.3	18	1.40	10.5%	0.66	0.85
2010	14.3	8.1	5	0.55	3.8%	0.76	0.89
2011	13.1	0.3	16	1.30	9.9%	0.66	0.87
2012	7.4	0.3	8	0.60	8.1%	0.67	0.90

Note: p_t^r, η_t and T given in €/tCO_2. F given in k€.

The selected annual values for F and T vary between 5 and 18 k€, and 0.55 and 1.40 €/tCO_2 (or 2.8 and 10.5% of the EUA price) across years.[56] To substantiate the improvement relative to zero trading costs on average across years (see Appendix 2.8 for graphical illustrations and more details in a given year), the selected cost pairs decrease the number of sorting errors by 40%, rationalize 70% of individual autarkic compliance decisions and reduce the dispersion across sorting error types as measured by a 160% increase in Shannon's entropy.

Although our approach to selecting trading costs differs from the various methods used in the related empirical literature, our results are in the same range. For instance, Naegele, 2018 estimates median and mean fixed permit market entry costs of 7 and 21 k€ across firms in Phase II, respectively.[57] Similarly, estimates of proportional trading costs are in the order of 0.1 € per permit traded but can go up to 2 € for small firms (e.g. Jaraitė, Convery, and Di Maria, 2010; Heindl, 2012b; Joas and Flachsland, 2016). Additionally, Frino, Kruk, and Lepone, 2010 and Medina, Pardo, and Pascual, 2014 find a bid-ask spread for Phase II futures contracts ranging from 1 to 10% of the EUA price, which can give a rough sense of the magnitude of proportional trading costs.

2.4.2 Supply control with vs. without trading costs

Trading costs affect equilibrium outcomes, which has important implications for policy design, evaluation and implementation. We thus utilize our calibrated model to appraise the market price responses to supply-curbing policies in the presence vs. absence of trading costs and how they depend on their incidence across firms.[58] We also evaluate how total compliance costs vary as supply is tightened depending on how firms change their trading behavior.

[56] As a robustness check, we increase (resp. decrease) all firms' baseline emissions by 5%. As expected, the calibrated η_t's are smaller (resp. larger). However, the resulting variation in the selected values for F and T is negligible relative to the reference case.

[57] See also Table 1 in Naegele, 2018 for a literature overview of transaction cost estimates in the EU ETS.

[58] This is a timely issue in a context where the Market Stability Reserve (MSR) is bound to reduce annual supply schedules in the short to mid term (e.g. Perino, 2018; Quemin and Trotignon, 2019a).

Impacts on market prices

We evaluate the price impacts of an arbitrary one-sixth tightening in (annual) supply in 2009 and 2012 for each select sample of firms.[59] We consider these two years because they feature negligible adjustment terms η_t and differing values for the trading cost pairs and market price levels p_t^r. We assume that permits are withdrawn directly from firms' allocations according to four alternative scenarios: (1) proportionally to their initial allocations, (2) uniformly across all firms, or uniformly across overallocated (3) or underallocated (4) firms exclusively. We take two alternative perspectives in this appraisal: one which is oblivious to the trading costs in the model calibration, the other in which trading costs are accounted for and selected as in Section 2.4.1. Our simulation results are reported in Table 2.3.

As expected, the incidence of the cutback across firms is neutral vis-à-vis the magnitude of the market price increase under the assumption of no trading costs. This is no longer the case when one accounts for trading costs: as Proposition 5 indicates, the magnitude of the market price increase, relative to the frictionless case, depends on a price effect and a distribution effect, i.e. how the tightening is distributed among firms.

Two findings emerge from our calibrated examples. First, the price increase is always larger when one accounts for trading costs than in the frictionless case, irrespective of the incidence scenario. This is because in our samples of firms some potential suppliers are autarkic due to the trading costs so that the market is initially tighter than in the frictionless case, which in turn tends to amplify the tightening-induced price increase. Additionally, the lower the price level to start with, the larger the relative tightening-induced price increase and the larger the absolute price increase in the absence vs. presence of trading costs – as previously hinted at in the analytical and numerical examples in Section 2.3.3. Relatedly and crucially, note that larger trading costs (as in 2009 w.r.t. 2012) should not be thought of as a sufficient condition to sustain larger price responses to a supply tightening.

Second, the incidence of the tightening has significant impacts on the resulting price increase, which can vary in size by 30-40% across incidence scenarios. Intuitively, we see that uniformly targeting the supply tightening on underallocated (resp. overallocated) firms leads to a larger (resp. smaller) price increase than when it is evenly distributed among all firms.[60] The lowest price increase obtains when the tightening is

[59] This is roughly the magnitude of the yearly reductions in auctions due to the MSR in 2019 and 2020, i.e. about 380 $MtCO_2$ for a total cap of about 1,850 $MtCO_2$ (European Commission, 2019). The magnitude of the tightening does not affect the qualitative nature of our results, see also Section 2.4.2.

[60] Given a fixed market price, when targeting underallocated firms (*i*) demand from buyers in $\mathcal{D}$ rises; (*ii*) some autarkic firms in $\mathcal{A}_2$ become buyers, increasing demand further; (*iii*) supply by sellers in $\mathcal{S}_3$

TABLE 2.3: Price responses to a $\frac{1}{6}$ supply tightening with different incidence scenarios

		Incidence scenario (1)	(2)	(3)	(4)
2009 (p^r=13.3)	$(p^\star - p^r)/p^r$	0.70	0.70	0.70	0.70
	$(\hat{p} - p^r)/p^r$	1.11	1.29	1.19	1.59
	$(\hat{p} - p^r)/(p^\star - p^r)$	1.59	1.84	1.70	2.27
2012 (p^r=7.4)	$(p^\star - p^r)/p^r$	1.04	1.04	1.04	1.04
	$(\hat{p} - p^r)/p^r$	2.14	2.47	2.27	2.79
	$(\hat{p} - p^r)/(p^\star - p^r)$	2.06	2.38	2.18	2.68

Note: p^r is the pre-tightening reference price in €/tCO_2, $p^\star$ (resp. $\hat{p}$) is the post-tightening price without (resp. with calibrated) trading costs. Incidence scenario: permits are withdrawn (1) proportionally to firms' allocations, uniformly across all (2), overallocated (3) or underallocated (4) firms in the annual samples.

spread across firms in proportion to their initial permit endowments, a proxy for their size under grandfathering-based allocation. As Section 2.4.2 will confirm with a welfare analysis, this incidence type leaves less (costly) reallocations to occcur through the market than the others (relative to the least-cost optimum). As such, it mitigates induced additional market strain and thus the resulting price increase.

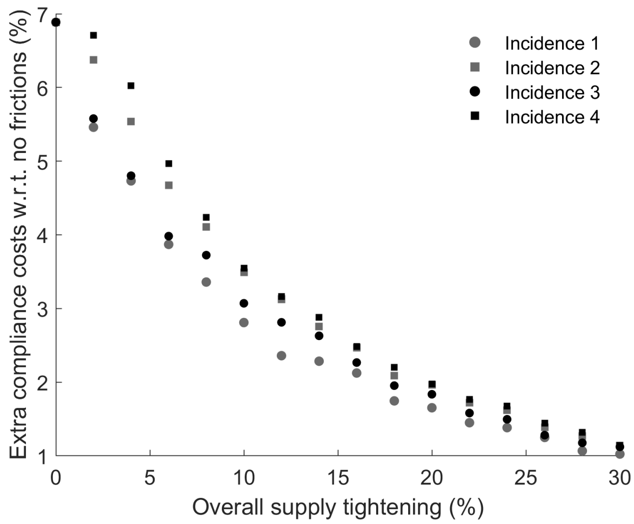
In summary, modeling assumptions (here considering trading costs or not) matter for supply policy evaluation (e.g. size of the price response) and implementation (e.g. role of the incidence on firms). Specifically, our simulation results suggest that a modeler/regulator who does not account for trading costs though they prevail in reality may underestimate the price impacts of supply-curbing policies, here by a factor of about two. This underestimation bias is slightly more pronounced the lower the pre-tightening price and varies with the incidence type.

Impacts on compliance costs

We evaluate compliance costs for a 0–30% range of tightening in supply for the 2009 select sample of firms and compare them depending on (1) whether trading costs are accounted for or not and (2) the type of incidence on firms. Overall compliance costs comprise abatement costs and incurred trading costs (if any) which we sum over all firms. By construction, they are increasing and convex in the stringency of the tightening and always higher in the presence of trading costs (Proposition 4). Relative to frictionless conditions, extra compliance costs result from incurred trading costs and foregone efficiency gains at the extensive and intensive margins. Figure 2.5 depicts these extra costs

declines and (*iv*) some of them become autarkic, reducing supply further. By contrast, only (*iii*) and (*iv*) applied to $\mathcal{S}_1 \cup \mathcal{S}_2$ occur when targeting overallocated firms.

FIGURE 2.5: Compliance costs for a 0–30% supply tightening with different incidence scenarios



Note: Based on the 2009 select sample of firms. Incidence scenario: permits are withdrawn (1) proportionally to firms' allocations, (2) uniformly across all, (3) overallocated or (4) underallocated firms.

in relative terms as a function of the stringency of the tightening with the same four types of incidence as in Section 2.4.2.

Two findings emerge from our simulations. First, the extra compliance costs attributable to trading costs are in the order of 7% with the reference supply. This figure should be taken as illustrative only because it results from a comparison of modeling outputs under different modeling assumptions, not from a proper counterfactual analysis which we by construction cannot perform in our framework. As supply is tightened, the relative extra compliance costs decrease as the associated increase in compliance costs in absolute terms gradually dwarfs the difference in compliance costs with and without trading costs.

Second, the incidence of the tightening has notable impacts on the size of the extra compliance costs, which are higher by 15 to 35% between the most and least welfare-deteriorating type of incidence. Although there are many moving parts, most of this wedge can be explained by the relative changes in the number of autarkic firms as supply is tightened across incidence types. Indeed, autarkic firms' compliance costs are invariant when supply varies, namely nil when they are overallocated, positive but constant when underallocated. Simulations reveal that the number of autarkic firms (mostly overallocated) is relatively stable under incidence type (1) while it immediately collapses under types (2) and (4) as they induce the largest changes in market structure (here, initial individual deficits/surpluses).[61] An incidence proportional to firms' allocations thus appears as the least distortive incidence type.

Finally, we note that for a given emissions cap stringency, the simulated market price level is commensurate with the market strain which is reflected in the size of unrealized gains from trade and incurred trading costs. That is, the ranking of incidence types in terms of welfare loss visible in Figure 2.5 is identical to that in terms of price level given in Table 2.3, specifically incidence type $(1) \succ (3) \succ (2) \succ (4)$ where $\succ$ denotes welfare dominance.

2.5 Conclusion

This paper advances the frontier of research on permit markets with transaction costs and makes three contributions to the literature. First, we develop a consolidation procedure for annual transaction and compliance data allowing us to scrutinize firms' market behavior over EU ETS Phase II. This reveals two important empirical facts, which we interpret as pointing to the existence of fixed and variable trading costs: autarkic behavior is pervasive, especially among small or long firms, and those firms that engage in trade do so quite sparsely and only for sufficiently large volumes. Second, we incorporate fixed and proportional trading costs in a standard permit market model. In our equilibrium framework, the permit price and firms' participation in and extent of trading are determined endogenously. This allows us to analyze the sensitivity of the equilibrium to shifts in the trading costs and firms' allocations, and we characterize the properties of the market price impacts, as they are generally ambiguous and can go both ways. Third, we calibrate our model to EU ETS Phase II transaction data and show how trading costs in the order of 10 k€ per annum plus 1 € per permit traded noticeably reduce the discrepancies between observations and theoretical predictions for firms' behavior. Our simulations also suggest that ignoring trading costs may lead modelers to underestimate the price impacts of supply-curbing policies, with the size of this underestimation bias notably hinging on the specific incidence of such policies on firms.

It is important to acknowledge the caveats one must apply when interpreting our results, two of which we wish to highlight as alleys for future research – see also Section 2.1.1 for a broader discussion. First, while our measure of transaction costs captures all sorts of frictions (or the resultant thereof) one should seek to formally disentangle

[61] The share of autarkic firms under a uniform targeting of overallocated firms is also stable at first before starting to drop at a 7% cutback. This separation between incidence types (1) and (3) is visible in Figure 2.5.

'hard' financial trading costs from 'soft' behavioral factors such as the endowment effect or rational inattention. Second, one should aim to refine the modeling of the market structure to formally account for the temporal trading dimension and the presence of non-compliance entities such as intermediaries in order to understand their interaction with transaction costs and market efficiency. The theoretical and quantitative caveats of our modeling framework notwithstanding, we believe that it is a valuable contribution in the direction of bringing models closer to practical realities, and as such, making them better equipped for policy design and evaluation.

Appendices of Chapter 2

2.6 Analytical derivations and collected proofs

2.6.1 Proof of Proposition 1

Given a market price $p > 0$, firm i's optimal abatement is $a_i^*(p) = p/\alpha_i$ and its individual efficiency gains from permit trading are defined by

$$G_i(p) = C_i(a_i^0) - \big(C_i(a_i^*(p)) + p(\beta_i - a_i^*(p))\big),$$

where $a_i^0 = \max\{0; \beta_i\}$. Recalling that $p_i^0 = \alpha_i a_i^0$ and $C_i(a_i) = \alpha_i a_i^2/2$, the above rewrites

$$\begin{aligned}
G_i(p) &= C_i(a_i^0) - \big(C_i(a_i^*(p)) + p(\max\{0;\beta_i\} + \min\{0;\beta_i\} - a_i^*(p))\big) \\
&= C_i(a_i^0) - \big(C_i(a_i^*(p)) + p(a_i^0 + \min\{0;\beta_i\} - a_i^*(p))\big) \\
&= \big((p_i^0)^2 - p^2 - 2pp_i^0 + 2p^2\big)/(2\alpha_i) - p\min\{0;\beta_i\} \\
&= (p_i^0 - p)^2/(2\alpha_i) - p\min\{0;\beta_i\} = (p_i^0 - p)^2/(2\alpha_i) + p\max\{0;-\beta_i\}.
\end{aligned}$$

Firm i is better off buying (resp. selling) permits when $p_i^0 > p$ (resp. $p_i^0 < p$) which defines the sets $\mathcal{D}$ and $\mathcal{S}$. Consequently, no firm is willing to buy (resp. sell) permits on the market when $p \geq \bar{\alpha}\bar{\beta}$ (resp. $p = 0$). Hence, a market price is feasible when $p \in (0; \bar{\alpha}\bar{\beta})$.

2.6.2 Proof of Lemma 1

For $\beta_i \leq 0$, i sells permits on the market if $G_i(p-T) - F > 0$, i.e. $X^2 - 2\alpha_i\beta_i X - 2\alpha_i F > 0$ with $X = p - T$. Only keeping the positive root, this occurs if $p - T > \alpha_i\beta_i + \sqrt{\alpha_i^2\beta_i^2 + 2\alpha_i F}$, which is nil for $F = 0$ and positive for $F > 0$.

For $\beta_i > 0$, i buys $(+)$ or sells $(-)$ permits on the market if $X^2 - 2\alpha_i(F + \beta_i X) + \alpha_i^2\beta_i^2 > 0$ with $X = p \pm T$. For a seller, we only keep the relevant root $X = p - T > \alpha_i\beta_i$ so i partakes in the market if $p - T > \alpha_i\beta_i + \sqrt{2\alpha_i F}$, which is always positive. For a buyer, we only keep the relevant root $X = p + T < \alpha_i\beta_i$ so i partakes in the market if $p + T < \alpha_i\beta_i - \sqrt{2\alpha_i F}$. This is positive provided that F is not too large, i.e. $F < \alpha_i\beta_i^2/2$. This must at least be true for the last potential buyer so $F < \bar{\alpha}\bar{\beta}^2/2$, see Lemma 2.

2.6.3 Proof of Proposition 2

Expanding firm i's market participation constraint $G_i(p \pm T) - F > 0$ gives

$$\begin{aligned}
&(p_i^0)^2 - 2p_i^0(p \pm T) + (p \pm T)^2 - 2\alpha_i(p \pm T)\min\{0;\beta_i\} - 2\alpha_i F > 0\\
\Leftrightarrow\ &\alpha_i^2(\max\{0;\beta_i\})^2 - 2\alpha_i(p \pm T)(\max\{0;\beta_i\} + \min\{0;\beta_i\}) - 2\alpha_i F + (p \pm T)^2 > 0\\
\Leftrightarrow\ &\alpha_i^2(\max\{0;\beta_i\})^2 - 2\alpha_i(\beta_i(p \pm T) + F) + (p \pm T)^2 > 0.
\end{aligned}$$

Substantiating the three different cases depending on the pairs (α_i, β_i), this rewrites

$$\begin{aligned}
\alpha_i^2\beta_i^2 - 2\alpha_i(F + (p+T)\beta_i) + (p+T)^2 > 0 &\text{ when } \alpha_i\beta_i > p + T,\\
\alpha_i^2\beta_i^2 - 2\alpha_i(F + (p-T)\beta_i) + (p-T)^2 > 0 &\text{ when } 0 < \alpha_i\beta_i < p - T, \text{ or}\\
-2\alpha_i(F + (p-T)\beta_i) + (p-T)^2 > 0 &\text{ when } \beta_i \leq 0.
\end{aligned}$$

When $\beta_i \leq 0$ (resp. $\beta_i > 0$) the α_i-thresholds obtain by solving a first-order (resp. second-order) polynomial inequality and keeping the relevant roots. When $\beta_i \leq -F/(p-T)$, the third inequality above holds for all $\alpha_i > 0$. This defines the sets $\mathcal{D}(p, F, T)$ and $\mathcal{S}(p, F, T)$.

We verify that $\mathcal{S}(p, F, T)$ (resp. $\mathcal{D}(p, F, T)$) effectively contains all selling (resp. buying) firms. To see this, observe that i is a seller (resp. buyer) i.f.f. $\beta_i - a_i^*(p - T) < 0 \Leftrightarrow \alpha_i < (p - T)/\beta_i$ (resp. $\beta_i - a_i^*(p + T) > 0 \Leftrightarrow \alpha_i > (p + T)/\beta_i$). This suffices to demonstrate our claim since i's thresholds can easily be shown to satisfy $\alpha_i^0, \alpha_i^- < (p - T)/\beta_i$ and $(p + T)/\beta_i < \alpha_i^+$.

Below, we provide the partial derivatives of the α-thresholds with their signs:

$$\begin{aligned}
\partial\alpha^\pm/\partial p = (1 \pm F/X_1^\pm)/\beta > 0 \quad & \partial\alpha^\pm/\partial\beta = -X_2^\pm(1 \pm F/X_1^\pm)/\beta^3 < 0\\
\partial\alpha^\pm/\partial F = (1 \pm X_3^\pm/X_1^\pm)/\beta^2 \gtrless 0 \quad & \partial\alpha^\pm/\partial T = (\pm 1 + F/X_1^\pm)/\beta^2 \gtrless 0\\
\partial\alpha^0/\partial p = (p-T)X_2^-/2(X_3^-)^2 > 0 \quad & \partial\alpha^0/\partial\beta = -(p-T)^3/2(X_3^-)^2 < 0\\
\partial\alpha^0/\partial F = -(p-T)^2/2(X_3^-)^2 < 0 \quad & \partial\alpha^0/\partial T = -(p-T)X_2^-/2(X_3^-)^2 < 0
\end{aligned}$$

where $X_1^\pm = \sqrt{F(F + 2(p \pm T)\beta)} > F$, $X_2^\pm = 2F + (p \pm T)\beta > 2F$ and $X_3^\pm = X_2^\pm - F > X_1^\pm$. This proves our claim on the changes in the measures of $\mathcal{D}(p, F, T)$ and $\mathcal{S}(p, F, T)$ as p, F or T increases. Note also that $\lim_{\beta \to 0^+} \alpha^+ = \lim_{\beta \to 0^+} 2F/\beta^2 = +\infty$. To get at $\lim_{\beta \to 0^+} \alpha^-$, we first compute the second-order Taylor expansion of the numerator in

α^-, namely

$$F + (p-T)\beta - F\left(1 + \frac{1}{2}\frac{2(p-T)\beta}{F} - \frac{1}{8}\left(\frac{2(p-T)\beta}{F}\right)^2\right) = \frac{(p-T)^2\beta^2}{2F},$$

so that $\alpha^- \sim_{\beta\to 0^+} (p-T)^2/(2F) = \alpha^0(p,F,T;0)$, i.e. there is continuity between α^- and α^0 in $\beta = 0$. By a similar token, $\partial\alpha^-/\partial\beta \sim_{\beta\to 0^+} = -(p-T)^3/2F^2 = \partial\alpha^0/\partial\beta(p,F,T;0)$, i.e. there is also continuity in slope. Finally, $\lim_{\beta\to 0^+} \partial\alpha^+/\partial\beta = \lim_{\beta\to 0^+} -4F/\beta^3 = -\infty$, $\lim_{\beta\to+\infty} \alpha^\pm = 0$, $\lim_{\beta\to -F/(p-T)} \alpha^0 = +\infty$ and $\lim_{\beta\to -F/(p-T)} \partial\alpha^0/\partial\beta = -\infty$, which completes the description of the behaviors of the supply and demand frontiers in Figure 2.3.

2.6.4 Proof of Lemma 2

A price is feasible as long as there is at least one buyer and one seller in the market. Hence (2.5) follows from Lemma 1 applied to the last potential buyer $(\bar{\alpha}, \bar{\beta})$ and seller $(\underline{\alpha}, \underline{\beta})$. Alternatively, the two price bounds obtain by solving $\alpha^0(p,F,T;\underline{\beta}) = \underline{\alpha}$ and $\alpha^+(p,F,T;\underline{\beta}) = \bar{\alpha}$. Trading costs are admissible if there exist feasible prices. From (2.5) this requires $\underline{\beta}\underline{\alpha} + T + \sqrt{\underline{\beta}^2\underline{\alpha}^2 + 2\underline{\alpha}F} < \bar{\alpha}\bar{\beta} - T - \sqrt{2\bar{\alpha}F}$ and $\bar{\alpha}\bar{\beta} - \sqrt{2\bar{\alpha}F} > p + T > 0$, which gives (2.4).

2.6.5 Proof of Lemma 3

First note that D and S are continuous and differentiable in p, F and T.

Partial derivatives w.r.t. p. D (resp. S) is strictly decreasing (resp. increasing) with p. In the case of D, it suffices to see that $p \mapsto y - (p+T)/x$ is strictly decreasing with p and that α^+ is strictly increasing with p. A similar argument follows for S, although the behavior of the second term in (2.6) is unclear as the bound $-F/(p-T)$ is increasing with p. To clarify, we compute the partial derivatives of the two terms of interest in (2.6) using Leibniz's rule in conjunction with Fubini's theorem. This yields

$$F/(p-T)^2 \int_{\underline{\alpha}}^{\bar{\alpha}} \big((p-T)/x + F/(p-T)\big) g(x|y = -F/(p-T)) h(-F/(p-T)) \mathrm{d}x$$
$$- F/(p-T)^2 \int_{\underline{\alpha}}^{\alpha^0} \big((p-T)/x + F/(p-T)\big) g(x|y = -F/(p-T)) h(-F/(p-T)) \mathrm{d}x,$$

which concludes since by Chasles' rule the above simplifies to

$$F/(p-T)^2 \int_{\alpha^0}^{\bar{\alpha}} \big((p-T)/x + F/(p-T)\big) g(x|y = -F/(p-T)) h(-F/(p-T)) \mathrm{d}x > 0.$$

Partial derivatives w.r.t. F. A qualitative argument as in the above could suffice but formal calculus will prove helpful in the following. Differentiating (2.7) and (2.6) w.r.t. F gives

$$\frac{\partial D}{\partial F} = -\int_0^{\bar{\beta}} \frac{\partial \alpha^+(p,F,T;y)}{\partial F}\big(y-(p+T)/\alpha^+(p,F,T;y)\big)g(\alpha^+(p,F,T;y)|y)h(y)\mathrm{d}y < 0,$$

$$\begin{aligned}\frac{\partial S}{\partial F} = &-1/(p-T)\int_{\underline{\alpha}}^{\bar{\alpha}}\big((p-T)/x+F/(p-T)\big)g(x|y=-F/(p-T))h(-F/(p-T))\mathrm{d}x\\ &+1/(p-T)\int_{\underline{\alpha}}^{\alpha^0}\big((p-T)/x+F/(p-T)\big)g(x|y=-F/(p-T))h(-F/(p-T))\mathrm{d}x\\ &+\int_{-F/(p-T)}^{0}\frac{\partial \alpha^0(p,F,T;y)}{\partial F}\big((p-T)/\alpha^0(p,F,T;y)-y\big)g(\alpha^0(p,F,T;y)|y)h(y)\mathrm{d}y\\ &+\int_0^{\bar{\beta}}\frac{\partial \alpha^-(p,F,T;y)}{\partial F}\big((p-T)/\alpha^-(p,F,T;y)-y\big)g(\alpha^-(p,F,T;y)|y)h(y)\mathrm{d}y.\end{aligned}$$

By Chasles' rule again, the first two terms in $\partial S/\partial F$ reduce to

$$-1/(p-T)\int_{\alpha^0}^{\bar{\alpha}}\big((p-T)/x+F/(p-T)\big)g(x|y=-F/(p-T))h(-F/(p-T))\mathrm{d}x \;<\; 0.$$

Thus $\partial S/\partial F < 0$ as the last two terms in $\partial S/\partial F$ are also negative.

Partial derivatives w.r.t. T. Similar arguments show that $\partial S/\partial T$ and $\partial D/\partial T$ are negative.

2.6.6 Proof of Proposition 3

The proof relies on the intermediate value theorem applied to $V = S - D$, which Lemma 3 shows to be continuous and strictly increasing with p.

Denote the upper (resp. lower) feasible price bound in (2.5) by $\bar{p}$ (resp. $\underline{p}$). Assume trading costs are admissible as in (2.4), thus $\bar{p} > \underline{p}$. By definition, $D(\bar{p},F,T) = 0$ since $\alpha^+(\bar{p},F,T;\bar{\beta}) = \bar{\alpha}$ and $\alpha^+ > \bar{\alpha}$ for all $0 < \beta < \bar{\beta}$ as α^+ is strictly decreasing with β. Because D is strictly decreasing with p, $D(p,F,T) > 0$ for any $p < \bar{p}$. Similarly, by definition $S(\underline{p},F,T) = 0$. Indeed the first integral in S is nil since $\underline{\beta} > -F/(\underline{p}-T)$; the second and third integrals are also nil since $\alpha^0(\underline{p},F,T;\underline{\beta}) = \underline{\alpha}$ so that $\alpha^0 < \underline{\alpha}$ and $\alpha^- < \underline{\alpha}$ for all $\beta > \underline{\beta}$ since α^0 and α^- are decreasing with β. Because S is strictly increasing with p, $S(p,F,T) > 0$ for any $p > \underline{p}$.

Therefore, $V(\underline{p},F,T) = -D(\underline{p},F,T) < 0$ and $V(\bar{p},F,T) = S(\bar{p},F,T) > 0$. The intermediate value theorem concludes: there exists $\hat{p} \in (\underline{p};\bar{p})$ such that $V(\hat{p},F,T) = 0$ and it is unique.

2.6.7 Proofs of analytical examples

After tedious but standard calculus (2.11) and (2.12) obtain by solving $D(p, F, 0) = S(p, F, 0)$ for p and $p^\star$ solves $D(p, 0, 0) = S(p, 0, 0)$. Below we sketch out the key steps of the computations for *Case 1* and omit those for *Case 2* as they follow the same lines. Define function J by

$$J = \hat{p}_1 + \frac{2F\sqrt{F(F+2\beta\hat{p}_1)}}{\beta^3(\bar{\alpha}-\alpha)} - p_1^\star,$$

which is constant (in specie, nil) according to (2.11). The implicit function theorem yields

$$\frac{\mathrm{d}\hat{p}_1}{\mathrm{d}F} = -\frac{\partial J/\partial F}{\partial J/\partial \hat{p}_1} \text{ and } \frac{\mathrm{d}\hat{p}_1}{\mathrm{d}\beta} = -\frac{\partial J/\partial \beta}{\partial J/\partial \hat{p}_1}.$$

One then has $\mathrm{d}\hat{p}_1/\mathrm{d}F < 0$ and $\mathrm{d}\hat{p}_1/\mathrm{d}\beta > 0$ as it is easy to check that $\partial J/\partial F > 0$, $\partial J/\partial \hat{p}_1 > 0$ and $\partial J/\partial \beta < 0$. In particular, it is convenient to rewrite the second equality above as follows

$$\frac{\mathrm{d}\hat{p}_1}{\mathrm{d}\beta}(1+\beta^2 X) = X(3F + 5\beta\hat{p}_1) + \frac{\mathrm{d}p_1^\star}{\mathrm{d}\beta} \text{ with } X = 2F^2/\big(\beta^4(\bar{\alpha}-\underline{\alpha})\sqrt{F(F+2\beta\hat{p}_1)}\big) > 0.$$

By linearity of $p_1^\star$ in β we have $\beta\frac{\mathrm{d}p_1^\star}{\mathrm{d}\beta} = p_1^\star$ so that it finally comes

$$\Big(\frac{\mathrm{d}\hat{p}_1}{\mathrm{d}\beta} - \frac{\mathrm{d}p_1^\star}{\mathrm{d}\beta}\Big)(1+\beta X^2) = X(3F + 5\beta\hat{p}_1 - \beta p_1^\star) \Rightarrow \frac{\mathrm{d}\hat{p}_1}{\mathrm{d}\beta} \geq \frac{\mathrm{d}p_1^\star}{\mathrm{d}\beta} \text{ iff } \hat{p}_1 \geq (p_1^\star - 3F/\beta)/5.$$

2.6.8 Proof of Proposition 5

We compute and determine the magnitudes of both the price and distribution effects in the face of a small variation in individual allocation levels accounting for induced changes at both the intensive and extensive margins. We study the two effects in turn.

Price effect. We aim to rank $\partial V(\hat{p}, F, T)/\partial p$ and $\partial V(p^\star, 0, 0)/\partial p$. We first note that

$$\frac{\partial D(\hat{p}, F, T)}{\partial p} = \underbrace{-\int_0^{\bar{\beta}}\int_{\alpha^+}^{\bar{\alpha}}(1/x)g(x|y)h(y)\mathrm{d}x\mathrm{d}y}_{\text{intensive margin} \leq 0}\underbrace{-\int_0^{\bar{\beta}}\frac{\partial \alpha^+}{\partial p}(y-(\hat{p}+T)/\alpha^+)g(\alpha^+|y)h(y)\mathrm{d}x\mathrm{d}y}_{\text{extensive margin} \leq 0},$$

where we omit the arguments in α^+ to reduce clutter. The intensive margin term captures the decrease in demand on the part of firms in $\mathcal{D}(\hat{p}, F, T)$. The extensive margin term captures the coexistent decrease in demand as the $\mathcal{A}_2$-$\mathcal{D}$ frontier moves to the northeast (see Figure 2.3). On that frontier the net demand $y - (\hat{p}+T)/\alpha^+$ is zero when $F = 0$ for any $T \geq 0$ since $\alpha^+ = (\hat{p}+T)/y$; and positive whenever $F > 0$ (specifically, firms enter or exit $\mathcal{D}$ with positive individual demands). This means that the extensive margin drops to zero when $F = 0$.

We proceed similarly for S, see Appendix 2.6.5 for some computation details. In total, we get

$$\frac{\partial V(\hat{p},F,T)}{\partial p} = \overbrace{\frac{\partial V(p^\star,0,0)}{\partial p} - \int_0^{\bar{\beta}} \int_{\alpha^-}^{\alpha^+} (1/x) g(x|y) h(y) \mathrm{d}x\mathrm{d}y - \int_{-F/(p-T)}^{0} \int_{\alpha^0}^{\bar{\alpha}} (1/x) g(x|y) h(y) \mathrm{d}x\mathrm{d}y}^{\text{intensive margin}}$$
$$+ \underbrace{\text{sum of positive terms}}_{\text{extensive margin}} \gtrless \frac{\partial V(p^\star,0,0)}{\partial p} = \int_{\underline{\beta}}^{\bar{\beta}} \int_{\underline{\alpha}}^{\bar{\alpha}} (1/x) g(x|y) h(y) \mathrm{d}x\mathrm{d}y.$$

When $F = 0$ the extensive margin effects are nil so $\partial V(\hat{p},0,T)/\partial p < \partial V(p^\star,0,0)/\partial p$, i.e. the price effect is above one. It can however be below one for some pairs $(F > 0, T)$ for which the extensive margin effects surpass those at the intensive margin. This is more likely to occur for small costs as the intensive margin terms decrease with the cost levels.

Distribution effect. Consider the collection of individual deficit shifts $\{\beta_i + \gamma(\beta_i)\}_i$ for some bounded function γ such that $|\gamma| \ll 1$. Subsequent demand D_t evaluated at $(\hat{p}, F, T)$ reads

$$D_t(\hat{p},F,T) = \int_0^{\bar{\beta}} \int_{\alpha^+(y_0+\gamma(y_0))}^{\bar{\alpha}} (y_0 + \gamma(y_0) - (\hat{p}+T)/x) g(x|y_0) h(y_0) \mathrm{d}x\mathrm{d}y_0,$$

where we omit the arguments in α^+ that are irrelevant for the proof to reduce clutter. Note that for all y_0 we can expand α^+ in powers of γ as follows

$$\alpha^+(y_0+\gamma(y_0)) = \alpha^+(y_0) + \gamma(y_0) \frac{\partial \alpha^+}{\partial y}\bigg|_{y=y_0} + \mathcal{O}(|\gamma(y_0)|^2).$$

Denoting equilibrium demand prior to small cap change by D_0, one gets

$$D_t(\hat{p},F,T) = D_0(\hat{p},F,T) + \int_0^{\bar{\beta}} \int_{\alpha^+(y_0)}^{\bar{\alpha}} \gamma(y_0) g(x|y_0) h(y_0) \mathrm{d}x\mathrm{d}y_0$$
$$- \int_0^{\bar{\beta}} \int_{\alpha^+(y_0)}^{\alpha^+(y_0)+\gamma(y_0)\frac{\partial \alpha^+}{\partial y}|_{y=y_0}} (y_0 + \gamma(y_0) - (\hat{p}+T)/x) g(x|y_0) h(y_0) \mathrm{d}x\mathrm{d}y_0 + \mathcal{O}(|\gamma(y_0)|^2).$$

The last line in the above expression can be approximated by

$$- \int_0^{\bar{\beta}} \gamma(y_0) \frac{\partial \alpha^+}{\partial y}\bigg|_{y=y_0} (y_0 - (\hat{p}+T)/\alpha^+(y_0)) g(\alpha^+(y_0)|y_0) h(y_0) \mathrm{d}x\mathrm{d}y_0 + \mathcal{O}(|\gamma(y_0)|^2),$$

where the approximation becomes exact in the limit as $|\gamma| \to 0$. Further assuming a uniformly distributed cap tightening, i.e. γ is constant and positive, $\lim_{\gamma\to 0}(D_t - D_0)/\gamma$ writes

$$\underbrace{\int_0^{\bar\beta}\int_{\alpha^+(y_0)}^{\bar\alpha} g(x|y_0)h(y_0)\mathrm{d}x\mathrm{d}y_0}_{\text{intensive margin}\geq 0} \underbrace{- \int_0^{\bar\beta} \frac{\partial\alpha^+}{\partial y}\bigg|_{y=y_0} (y_0 - (\hat p + T)/\alpha^+(y_0))g(\alpha^+(y_0)|y_0)h(y_0)\mathrm{d}x\mathrm{d}y_0}_{\text{extensive margin}\geq 0}$$

as $\lim_{\gamma\to 0}\mathcal{O}(\gamma) = 0$. The intensive margin term captures the increase in demand on the part of firms in $\mathcal{D}$ prior to the tightening. The extensive margin term captures what happens at the $\mathcal{A}_2$-$\mathcal{D}$ frontier, i.e. the novel demand on the part of firms exiting $\mathcal{A}$ and entering $\mathcal{D}$. Note again that the extensive margin component drops for any $T \geq 0$ when $F = 0$.

We proceed similarly for S (computations are longer but follow the same logic). Then, all the terms in $\lim_{\gamma\to 0}(V_t - V_0)/\gamma$ can be grouped into two categories, namely

$$\lim_{\gamma\to 0}(V_t(\hat p, F, T) - V_0(\hat p, F, T))/\gamma = \underbrace{|\mathcal{I}| - |\mathcal{A}(\hat p, F, T)|}_{\text{intensive margin}} + \underbrace{\text{sum of positive terms}}_{\text{extensive margin}} \gtrless |\mathcal{I}|,$$

where $|\mathcal{I}| = \lim_{\gamma\to 0}(V_t(p^\star, 0, 0) - V_0(p^\star, 0, 0))/\gamma$. Roughly put, the larger the set of autarkic firms, i.e. the larger the trading costs, the more likely the distribution effect is below one, i.e. $\lim_{\gamma\to 0}(V_t(\hat p, F, T) - V_0(\hat p, F, T))/\gamma < |\mathcal{I}|$ holds. With $F = 0$, this holds for all $T > 0$.

Finally, we consider alternative distributions of supply tightening in the intensive margin only case treated in the body of the paper. When uniformly distributed among all firms, $\mathrm{d}\beta_i = \mathrm{d}\mathcal{Q}$ holds for all $i \in \mathcal{I}$. When uniformly targeted on all firms with positive (resp. negative) deficits, $\mathrm{d}\beta_i = \mathrm{d}\mathcal{Q}/(|\bar{\mathcal{S}}_3| + |\bar{\mathcal{D}}| + |\bar{\mathcal{A}}_2|) > \mathrm{d}\mathcal{Q}$ (resp. $\mathrm{d}\beta_i = \mathrm{d}\mathcal{Q}/(|\bar{\mathcal{S}}_1| + |\bar{\mathcal{S}}_2| + \bar{\mathcal{A}}_1|) > \mathrm{d}\mathcal{Q}$) holds for all i with $\beta_i > 0$ (resp. $\beta_i < 0$) where the sets $\mathcal{S}_k$ and $\mathcal{A}_k$ are defined in Figure 2.3 and the upper bar is a shorthand meaning 'evaluated at $(\hat p, F, T)$'. In these three cases the distribution effect is

$$\begin{aligned} &(|\bar{\mathcal{S}}_1| + |\bar{\mathcal{S}}_2| + |\bar{\mathcal{S}}_3| + |\bar{\mathcal{D}}|)/|\mathcal{I}| < 1, \\ \text{or } &(|\bar{\mathcal{S}}_3| + |\bar{\mathcal{D}}|)/(|\bar{\mathcal{S}}_3| + |\bar{\mathcal{D}}| + |\bar{\mathcal{A}}_2|) < 1, \\ \text{or } &(|\bar{\mathcal{S}}_1| + |\bar{\mathcal{S}}_2|)/(|\bar{\mathcal{S}}_1| + |\bar{\mathcal{S}}_2| + |\bar{\mathcal{A}}_1|) < 1. \end{aligned}$$

The magnitude of the price increase in the face of a given supply tightening thus depends on the way it is allocated among firms. The ranking between the three incidence types presented above is unclear prima facie: it hinges on the levels of the trading costs F and

T and on the distributions of the firms' characteristics $\{\alpha_i\}_i$ and $\{\beta_i\}_i$.

2.7 Consolidation methodology

Data recorded in the European Union Transaction Log (EUTL) contains both compliance and trading related information (at the account level) in two separate databases: the compliance database keeps track of the initial allocation and reconciliation of allowances; the transaction database records every physical exchange completed across accounts (including the account holder names of trading parties, date and volume traded). There are three main categories of accounts: Operator Holding Accounts (OHAs, one per regulated installation), Person Holding Accounts (PHAs) and Trading Accounts. The latter two can be opened and managed by non-regulated entities with no compliance obligations (e.g. intermediaries, financiers).

These two databases need to be consolidated at the company level – the relevant granularity level for abatement, compliance, trading and wider economic decisions. However, two issues arise when trying to match accounts to parent companies. First, only limited or incomplete information is available on the firms and sectors associated to each account. For instance, no dedicated field in the account characteristics indicates the name of a parent company, when it exists (e.g. account holders must fill an 'Account Holder Name' field but it is uneven across accounts as to the precision of company-specific details). Second, there is no key to match the two databases so we need to create our own beforehand.

To get at the ownership structure within the EUTL, we first construct a list of parent company names from the compliance database which we then use as a key to consolidate the trading information from the transaction database at the company level. To that end, we first clean the 'Account Holder Name' fields in the compliance database, totaling about 17,000 accounts over all years. Specifically, we remove punctuation marks, prefixes, suffixes, etc and separate words. We then run a first round of matching for duplicates on the first word the character strings contain, and obtain a first-pass list which associates the so-extracted parent companies to their accounts. We gradually refine the list by repeating this procedure with the second, third and fourth words for the remaining unassigned accounts.

In practice, a company name – when explicitly specified – often appears in the first or second word of the search field so that our simple method allows us to get a reasonably goof idea of which company owns which accounts. After the fourth iteration of the matching procedure, around 10% of accounts are single. We manually assign them to a

TABLE 2.7.1: Descriptive statistics for consolidated regulated firms (2009 sample)

Trading firms

Sector	Number of firms	⟨Number⟩ of accounts	% of total emissions	Median deficit	⟨Number⟩ of transactions	⟨Volume⟩ of transactions
Combustion	872	2.6	71.2	70,654	15.8	39,517
Refining	23	4.0	8.5	72,063	10.9	211,449
Metallurgy	37	3.4	3.2	-114,510	6.8	218,805
Cement & Lime	344	3.1	15.1	-25,474	5.5	34,095
Chemicals	8	3.1	0.2	-11,056	6.1	52,201
Paper & Glass	164	2.6	1.6	-8,272	8.3	23,242
Other	3	6.0	≈ 0	-5,600	4.0	1,494

Total number of observations: 1451.

Autarkic firms

Sector	Number of firms	⟨Number⟩ of accounts	% of total emissions	Median deficit
Combustion	848	2.3	62.6	3,665
Refining	14	2.1	11.0	267,178
Metallurgy	41	2.0	3.7	-52,835
Cement & Lime	165	2.3	13.6	-7,749
Chemicals	4	2.0	1.2	-13,266
Paper & Glass	217	2.4	8.9	-3,114
Other	1	1.0	≈ 0	-11,139

Total number of observations: 1290.

Note: Median deficits and average volumes of transactions given in tCO_2. $\langle \cdot \rangle$ denotes the average.

parent company (e.g. with dedicated web searches) and those for which manual matching is unsuccessful remain single. Our final parent company list contains 7,215 entries in total over Phase II (2008-2012).

In parallel, a total of 7,210 accounts recorded some trading activity (at least one exchange) in the transaction database over Phase II, some of which with no compliance obligations. Only considering compliance entities reduces the transaction database to 5,145 active accounts. This essentially amounts to keeping OHAs, or PHAs opened and run by a regulated company (typically to first pool allocations and later dispatch EUAs for compliance). Figure 2.1 is based on this select database, where (1) a compliance entity is deemed autarkic if it records no trade with compliance or non-compliance entities alike; (2) year-on-year changes in the number of observations occur due to installation/account closures and new entries as they occur.

We cross-check our consolidation outputs with those in Jaraitė-Kažukauskė and Kažukauskas, 2015, Naegele, 2018 or Hintermann and Ludwig, 2018 who link EUTL accounts to the Orbis database (Bureau van Dijk) to match installations to parent companies. Their methodologies are similar to that underpinning the Ownership Links and Enhanced EUTL Dataset, hosted by the European University Institute. Although we were not aware of this publicly available database linking accounts to parent companies when we started our project, it allows us to perform an ex-post sanity check for our consolidation methodology. Our respective results are found to be similar, e.g. Naegele finds a close 4,578 firms with her method.

The Illustration requires us to merge the compliance and transaction databases as we want the allocation, verified emissions and trading activity at the regulated firm level. Because the 'Account Holder Name' field is present in both databases, this is in principle straightforward. Due to matching discrepancies, however, the merged database only contains 2,500 entries. It is used to plot Figure 2.2 but needs further cleaning to be used in the Illustration. Specifically, we exclude firms whose reported information is anomalous (e.g. emissions are nil) or missing (e.g. no allocation nor market position provided). This leads to slight changes in the number of yearly entries. Table 2.7.1 below draws on these datasets. Finally, we remove firms with implied negative abatement and our yearly datasets are ready for use. This leads, again, to slight changes in the number of yearly entries, see Table 2.8.1 for descriptive statistics.

2.8 Calibration results

This Appendix provides additional details on the model parametrization (Section 2.4.1) and the selection of trading costs (Section 2.4.1). Specifically, Table 2.8.1 provides basic descriptive statistics to help visualize the annual $\{\alpha_{i,t}, \beta_{i,t}\}_{i,t}$ inference outputs and Figure 2.8.1 graphically depicts how our cost selection criteria evolve with F and T for the year 2009.

TABLE 2.8.1: Annually inferred firms' characteristics (rounded)

	Year	#Firms	Min	Max	Mean	Median	% Positive
α	2008	1,868	$2.1\cdot10^{-6}$	59	$9.4\cdot10^{-2}$	$7.1\cdot10^{-3}$	100
	2009	1,954	$1.3\cdot10^{-6}$	13	$2.9\cdot10^{-2}$	$3.6\cdot10^{-3}$	100
	2010	1,378	$1.6\cdot10^{-6}$	43	$7.1\cdot10^{-2}$	$5.1\cdot10^{-3}$	100
	2011	1,592	$3.8\cdot10^{-6}$	11	$5.6\cdot10^{-2}$	$5.5\cdot10^{-3}$	100
	2012	1,496	$3.4\cdot10^{-6}$	22	$4.5\cdot10^{-2}$	$3.1\cdot10^{-3}$	100
β	2008	1,868	$-4.0\cdot10^{6}$	$1.9\cdot10^{7}$	$23\cdot10^{3}$	-29	49
	2009	1,954	$-2.8\cdot10^{6}$	$2.2\cdot10^{7}$	$50\cdot10^{3}$	39	51
	2010	1,378	$-7.7\cdot10^{6}$	$1.8\cdot10^{7}$	$17\cdot10^{3}$	-1,100	38
	2011	1,592	$-2.2\cdot10^{6}$	$1.4\cdot10^{7}$	$26\cdot10^{3}$	-320	46
	2012	1,496	$-4.9\cdot10^{6}$	$7.5\cdot10^{6}$	$30\cdot10^{3}$	810	59

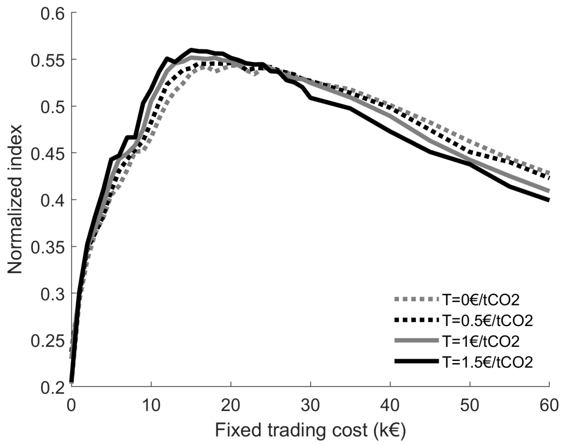
Note: α given in €/$(tCO_2)^2$ for $T = 0$. β given in tCO_2, not adjusted for year-on-year bank variations.

Let us elaborate on Figure 2.8.1. As F and/or T increase the proportion of observed autarkic firms sorted as autarkic by the model increases (type 3-4 errors decrease). However, higher trading costs also imply that the model sorts more observed trading firms as autarkic (type 1-2 errors increase). As a result, for every value of T, Shannon's entropy hence has an inverted U shape and is maximal at some intermediate value of F. In turn, since the total number of errors is relatively stable, index variations are primarily driven by the entropy component – note that it can be locally non-concave due to the discrete nature of our problem.

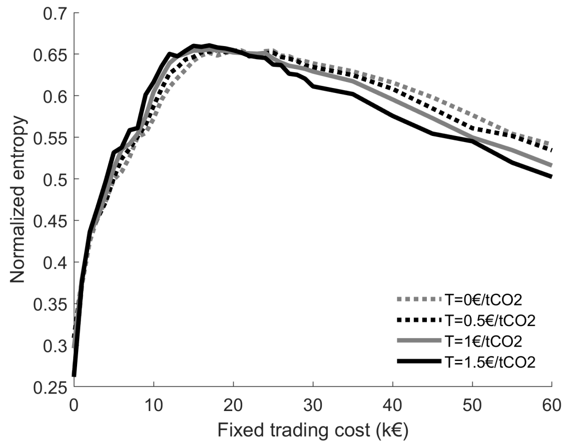
We see that curves in Figure 2.8 are ranked by increasing T values, i.e. the higher F and/or T the more autarkic compliance decisions are replicated by the model. In Figure 2.8.1 this ranking only holds when F is not too large – specifically before the crossing in Figure 2.8. After this point, the ranking is reversed as an increase in F and/or T increases the imbalance between type 1-2 and type 3-4 sorting errors.

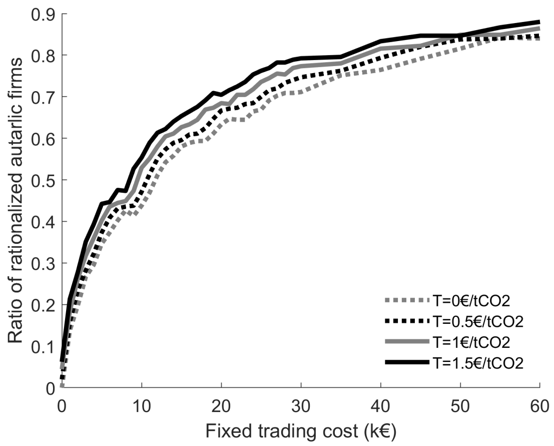
FIGURE 2.8.1: Selection criteria as functions of F and T (2009 sample)

(A) Normalized index

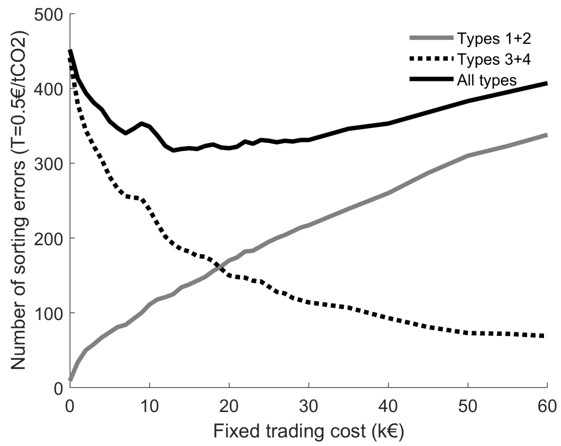


(B) Normalized entropy





(C) Ratio of rationalized autarkic firms



(D) Number of sorting errors (T=0.5€/tCO_2)

Chapter 3

Technological progress and carbon price formation

This chapter is the result of a collaboration with Marc Baudry

* * *

3.1 Introduction

The role of technological progress in a pollution-constrained world has mostly been studied through the prism of 'induced' technological change. First developed by J.R. Hicks in the context of the labor market, it states that technological progress will benefit more some inputs than others, according to their relative prices. In his words, *"A change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind - directed to economising the use of a factor which has become relatively expensive"* (Hicks, 1932). Assuming factor-augmenting technologies, Acemoglu, 1998; Acemoglu, 2002; Acemoglu, 2007 then formalized that market mechanisms can, by altering input prices, lead to biased technological change in turn. Economists being increasingly concerned with environmental problems like global warming, it was soon showed that an environmental policy can also influence the direction of technological change towards 'cleaner' inputs (Acemoglu et al., 2012) or low carbon innovation (Grubb, Duong, and Chapuis, 1994; Goulder and Schneider, 1999; Gerlagh, Kverndokk, and Rosendahl, 2009), with consequences on the design of CO_2 abatement policies (Goulder and Mathai, 2000).

However, the induced technological change doctrine restricts technological progress to those technologies which lower the cost of CO_2 abatement. Due to low carbon prices until the late third trading period (2013-2020), little attention has been paid to the response of technological progress to the European Union Emissions Trading Scheme (EU-ETS) in turn. The few studies analyzing the causal impact of the EU-ETS on technological advances did so with a focus on low-carbon patenting and R&D expenditure (Borghesi et al., 2015; Calel and Dechezleprêtre, 2016; Calel, 2020). Moreover, the feedback effect of technological progress on carbon price formation and policy design has never been considered, to our knowledge, in the theoretical and empirical literature on the EU-ETS. The much studied price slump that occurred in the second trading period (2008-2012) has mainly been attributed to a supply imbalance indeed (De Perthuis and Trotignon, 2014; Ellerman, Valero, and Zaklan, 2015), and econometric studies identified energy prices (Creti, Jouvet, and Mignon, 2012; Koch et al., 2014), renewable energy supply and weather variation (Alberola, Chevallier, and Chèze, 2008; Rickels, Görlich, and Peterson, 2015), political events and announcements (Hitzemann, Uhrig-Homburg, and Ehrhart, 2015; Koch et al., 2016), banking of allowances (Hintermann, 2010), or hedging and speculation (Friedrich et al., 2020; Tietjen, Lessmann, and Pahle, 2020) to be the main carbon price drivers.[1]

In the context of the EU-ETS, we argue that the induced-technological-change bias could have led to miss half of the picture, by concealing the role of technological progress in carbon price formation. By contrast to Acemoglu's stand, Salter et al., 1969 raised that firms' primary objective is to *"[...] seek that invention which yields the greatest increment to profits."* indeed, with no particular reason to favor the relatively more expensive factor. Therefore, and in line with the first models of technological progress (Romer, 1990; Aghion and Howitt, 1990), this study revisits the topic of technological progress in the EU-ETS with the most general approach possible. More precisely, our approach departs from the induced technological change literature as we do not make any preliminary assumption about the nature of technological progress. We therefore consider any improvements of regulated plants' total factor productivity which can affect the carbon market's fundamentals, namely marginal costs of abatement, and investigate their effect on carbon price formation.

This study focuses on six manufacturing industries covered under the EU-ETS over the 2013-2017 period, plus the power sector, and proceeds in three structuring steps. First, and on the basis of the technological frontier framework developed by Shephard, 1970, we develop a measure of technological progress experienced by plants over the years. Departing from a binary, clean *versus* dirty technological adoption, this approach enables us to characterize technological progress without any presupposition about its nature, and information about the price of production factors. As a characterizing criterion, we define *non-directed* technological progress to increase both carbon intensity of production and baseline emissions under *laisserfaire* conditions. By contrast, technological progress is referred to as *directed* when the carbon intensity of production decreases. As

[1] A comprehensive review can be found in Hintermann, Peterson, and Rickels, 2016.

sub-cases, *strongly* (*weakly*) *directed* technological progress results in decreasing (increasing) baseline emissions. Using a directional distance function method (Chung, Färe, and Grosskopf, 1997), we calibrate industry technological frontiers on plant input and output data from the European Union Transaction Log[2] and the Amadeus[3] databases. Our results reveal that on average, technological progress mostly led to inflate plants' baseline, i.e. $laisser faire$ emissions, and lower the carbon intensity of production, which we qualify as *weakly directed*. Therefore, we find that plants primarily seek total factor productivity gains despite the environmental regulation, putting in perspective the induced technological change literature.

Second, calibrated technological frontiers enable us to compute annual, parametric marginal abatement cost (m.a.c.) curves at the industry level, based on a revenue-maximization program. Therefore, we contribute to the empirical literature on m.a.c. estimation in the EU-ETS, which mainly relies on the outputs of macroeconomic models (Landis, 2015), or *ad-hoc* calibration methods (Baudry, Faure, and Quemin, 2019; Beck and Kruse-Andersen, 2018; Quemin and Trotignon, 2019a). By contrast to these methods, our approach to estimate m.a.c. curves requires little assumptions about the structure of the markets for products and pollutants, and has modest data requirements. Consequently, we argue that it could provide a practical alternative to the benchmarking procedure, currently used to determine the size of plants' free permit endowment in the EU-ETS. The analysis of m.a.c. curves' then reveals that great differences in magnitude between high and low carbon intensity industries. Specifically, a realistic price of carbon would trigger a much greater abatement effort in highly carbon-intensive industries that in low carbon intensity ones. Furthermore, the nature of technological progress greatly affects the amount of abatement that can be realized at a given price, because of its effect on aggregate baseline emissions. Specifically, baseline-inflating (resp. deflating) technological progress contributes to increase (resp. decrease) emissions reductions.

Third, numerical m.a.c. curves enable us to analyze the transmission of technological progress to the annual market price of carbon from 2013 to 2017. More precisely, we use allocation data from the EUTL to compute the permit supply of the considered production sites, and then isolate the impact of technological progress on the market clearing price. Interestingly, and since baseline-inflating technological progress is dominant in our samples, it results in increasing the market clearing price above its historical levels, by 1.9-38€/tCO_2. The analysis of industries' net permit demand in equilibrium also

[2]The emissions and transactions electronic registry of the EU-ETS
[3]From Bureau Van Dijk, which records financial plant data

reveals significant permit transfers from low to high carbon-intensity industries. Consequently, our results suggest that technological progress which is not *strongly directed* by nature tightens the effective emissions constraint, and increases the financial burden of highly carbon intensive industries, which has important policy implications.

The remainder is organized as follows: Section 3.2 presents the technological frontier framework and our modeling approach of marginal abatement cost curves, Section 3.3 presents the data and the directional distance function calibration method, Section 3.4 conducts an efficiency analysis of selected industries and discusses the dynamics of marginal abatement cost curves, Section 3.5 presents the market equilibrium and analyzes the impact of technological change, and Section 3.6 discusses policy implications.

3.2 Theoretical framework

3.2.1 Technological frontiers

In this study, the production of manufacturing goods is considered to be a multi-input, multi-output process, involving the production of both good (e.g. cement) and bad (e.g. greenhouse gases) outputs. First introduced by Shephard, 1970, and generalized by Chambers, Chung, and Färe, 1998 to accommodate a multi-output framework, the relationship between inputs and outputs may be characterized by a production set containing all combinations of goods and bads which can be obtained from a given set of inputs (Coelli et al., 2005). Considering a vector x of inputs, a vector y of good outputs (i.e. production) and a vector b of bad outputs (i.e. pollutants), a production technology set $P(x)$ of a plant can be defined as

$$P(x) = \{(y, b) : x \text{ can produce } (y, b)\}$$

According to classical micro-economic assumptions, the representation of $P(x)$ exhibits the following properties

- production requires a positive level of inputs : $P(0) = (0, 0)$.
- the size of the set cannot decrease if more inputs are used: $x' \geq x$ implies $P(x) \subseteq P(x')$.
- desirable outputs can be disposed at no cost: $y' \leq y$ implies $(y', b) \in P(x)$.
- good and bad outputs are jointly produced: if $b = 0$, $y = 0$.
- bad outputs cannot be freely disposed: $0 \leq \theta \leq 1$ leads to $(\theta y, \theta b) \in P(x)$.

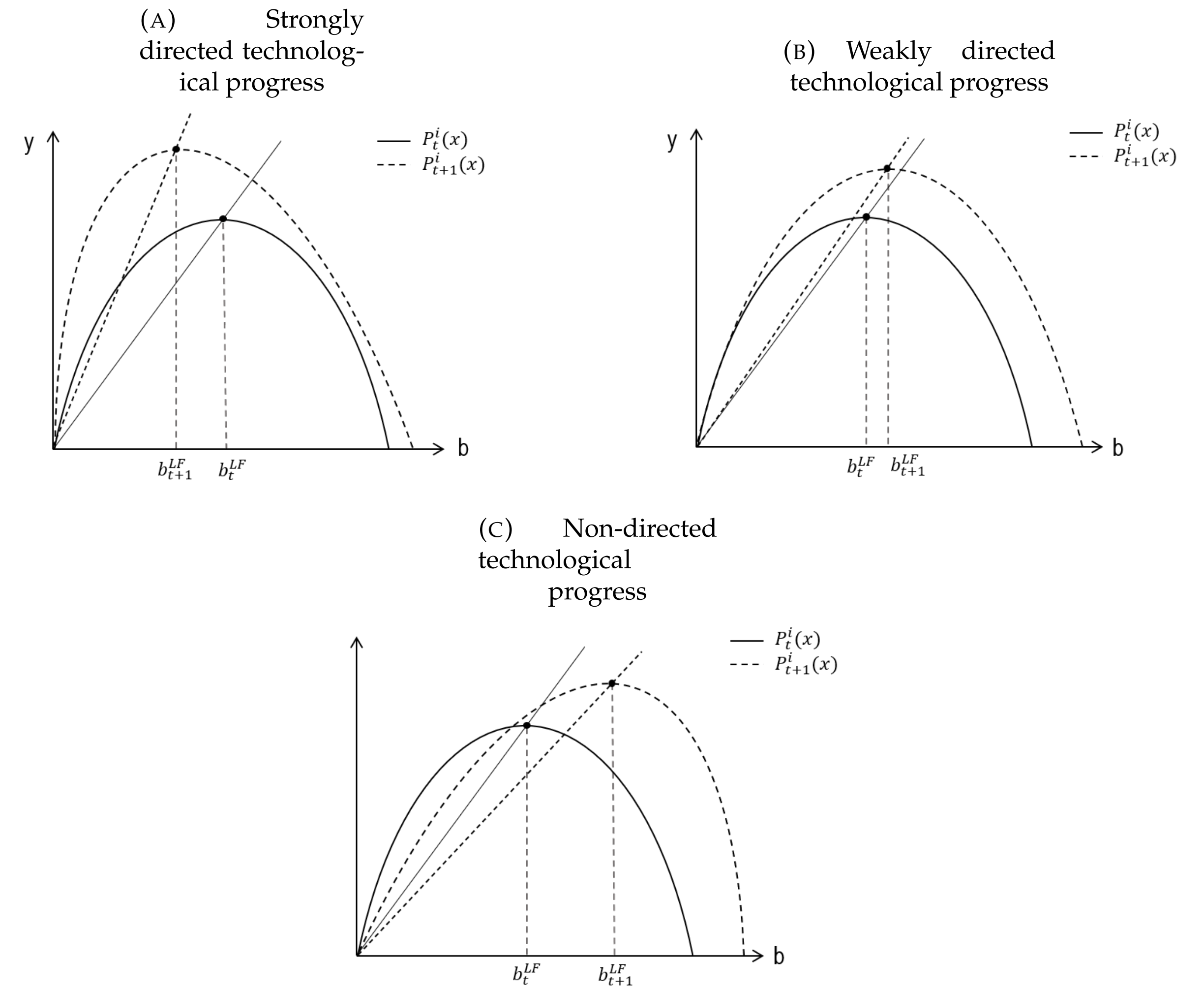
The production set is closed by a so-called technological frontier, which reflects the current state of technology of a producing plant. Technological progress may then be characterized by an expansion of the technological frontier, i.e. an increase in total factor productivity, keeping inputs constant.

In the case of a single good and bad output, Figure 3.2.1 illustrates the technological structure of a plant which experiences technological progress at $t+1$ (dashed curve). Although this approach enables us to represent a wide range of improvements in (b, y) combinations, we select a criterion to qualify the nature of technological progress for the purpose of this study. We choose to base this criterion on changes in the carbon intensity of production, rather than in the absolute level of pollution b, for its greater flexibility and realism. More precisely, we are concerned with the direction of the change in the carbon intensity of production due to technological progress at maximum y, i.e. with no constraints on pollution. Graphically, this corresponds to comparing positions of radius of the (b, y) orthant passing through the top of the technological frontiers at t and $t+1$. Indeed, as detailed *infra*, the summit of a technological frontier corresponds to the optimal, revenue-maximizing choice under $laisserfaire$ conditions, and thus characterizes the carbon intensity (i.e. the slope of the radius) associated to the technology.

Figure 3.2.1 illustrates the three natures of technological progress. In panel (C), technological progress increases both the carbon intensity of production and baseline emissions, which we refer to as *non-directed* technological progress. By contrast, panel (A) and (B) characterize *directed*, i.e. carbon-intensity decreasing technological progress. Note that, although *non-directed* technological progress unequivocally results in increasing the $laisserfaire$ pollution level b^{LF}, the case of *directed* technological progress is not straightforward. The latter can lead to either decrease or increase baseline emissions indeed. To clarify this difference, we therefore distinct *strongly* and *weakly directed* technological progress, which respectively result in decreasing (panel (A)) or increasing (panel B) the level of $laisserfaire$ pollution b^{LF}. In practice, an example of *strongly directed* technological change in the cement industry can be the switch to a waste-heat recovery system,[4] which enables to increase the productivity of energy, thus decreasing the carbon-intensity of production. By contrast, the replacement of an old limestone grinder can avoid raw material losses and lead to increase output-per-capita, without changing the carbon intensity of cement. In our framework, this corresponds to *weakly directed* technological change.

[4]High-performing coolers make it possible to recover the excess heat during the clinker cooking process for electricity generation.

FIGURE 3.2.1: Nature of technological progress



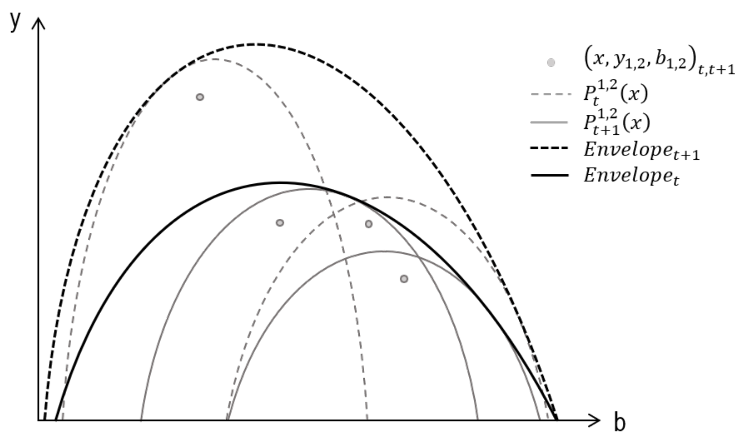
Note: $P_t^i(x)$ and $P_{t+1}^i(x)$ denote the technological frontier of plant i at t and $t+1$, respectively. b_t^{LF} and b_{t+1}^{LF} denote *laisserfaire* emissions at t and $t+1$.

The nature of technological progress being defined at the *micro*, plant level, measuring it requires to move to a *meso* level of analysis. Indeed, a technological frontier can only be quantified with multiple points. Therefore, and conforming to the theoretical framework, we have to consider a set of plants sharing the same technology in order to characterize an industry technological frontier, which can be estimated as detailed in Section 3.3.

Letting two plants 1 and 2 use the same quantity of inputs x, the production sets $P_t^1(x)$ and $P_t^2(x)$ can be represented in the bi-dimensional space (b, y), as in Figure 3.2.2. Their respective combination of good and bad outputs correspond to the empty and full grey dots. First, note that plants operate below their technological frontier in our representation, which reveals some scope for technical efficiency improvements, namely production technique enhancements (e.g. plant management, organization of the production line) given the state of technology and set of inputs. Second, both plants experience technological progress between t and $t+1$, as their production sets $P_t^1(x)$ and $P_t^2(x)$ expands over-time. Consequently, the new production technology enables them to make more out of an unchanged set of inputs, in terms of quantity of desirable output y. Furthermore, plant 2's technology is dominated by plant 1's despite technological progress. For any b indeed, the maximum production level y is greater at both t and $t+1$ for plant 1. Note that technological progress, characterized by a displacement of the frontier, is independent from technical efficiency which relates to the distance to the frontier.

In the same way as at the plant level, the three natures of technological progress (i.e *strongly* or *weakly directed*, and *non-directed*) can then be characterized at the industry level. To do so, we define an envelope curve which embodies plants' production sets in a single, industry super-set (plain and dashed black curves in Figure 3.2.2). The envelope curve at $t+1$ captures all technological changes that occurred at the plant level in turn. Comparing carbon intensities at the top of the envelope curve at t and $t+1$ then enables us to characterize the type of technological progress experienced in aggregate. In the illustration, technological change at the industry level is *strongly directed*.

FIGURE 3.2.2: Plant and industry technological frontiers



Note: Representation at t and $t+1$ of the production sets $P(x)$ of two producing plants producing one desirable good and one pollutant, y and b, and using x inputs.

3.2.2 Marginal abatement cost curves

Having characterized technological progress, we can now compute the marginal abatement cost (m.a.c.) of plants that are subject to a pollution constraint. We define m.a.c. in line with textbook environmental economics, which state profit-maximizing producers trade-off sales revenue from the production of goods with the cost of complying with the environmental regulation (Tietenberg and Lewis, 2016). Our approach thus substantially differs from that of expert based m.a.c. curves like McKinsey's (McKinsey, 2009), who analyze the cost merit order of abatement options relying on the adoption of low-carbon technologies or energy-efficiency measures. More precisely, the technological frontier method enables us to consider two ways of carry out emissions reductions visible on Figure 3.2.2. On the one hand, a plant can abate by reducing its production level y, thus leading to a financial sacrifice. On the other hand, it can switch to another, 'cleaner' technology, as if plant 1 adopted plant 2's technology (plain grey lines on Figure 3.2.2). Such costs of technological adoption corresponds to abatement costs *a la* McKinsey. Yet, note that *micro* technological changes are hidden in our *meso* analysis.

More precisely, in presence of an individual cap on emissions, a plant's cost of compliance is equivalent to the decrease in sales revenue due to required emissions reductions. The corresponding abatement cost may then be measured by comparison to the *laisser-faire* situation. Thus, m.a.c. can be defined as the foregone revenue associated with the tightening of the pollution constraint by one additional unit. When the environmental regulation takes the form of a market based instrument, such as an emissions trading scheme or a tax on emissions, m.a.c. directly guide plants' production choices. For instance, polluting plants will optimally emit until the marginal abatement effort is as costly as the permit price on the emissions trading scheme, or as the unitary tax.

Formally, the objective of a polluting plant i selling its production y on the goods market is

$$\max_{y,b} R_i = p_y y_i \quad \text{s.t} \quad (b_i, y_i) \in P_i(x)\ ,\ b_i \leq \bar{b_i}$$

where revenue-generating production necessarily involves a polluting by-product b. All plants are assumed to be price takers on the goods market. Besides, inputs are fixed according to the technological frontier framework presented in Section 3.2.

Under $laisserfaire$ conditions, $\bar{b_i}$ does not bind, hence the producer faces an unconstrained revenue maximization problem. The solution corresponds to the level b_i^{LF}, also referred to as baseline emissions, which satisfies $f_i'(b) = 0$ where f_i denotes the functional expression of the technological frontier in the (b, y) space. Graphically, the (y_i^{LF}, b_i^{LF}) coordinates correspond to the top of the technological frontier (see Figure 3.2.3). In presence of an environmental regulation however, $b \leq \bar{b}$ is binding. The optimal level of abatement of plant i can thus be defined as $a_i = b_i^{LF} - b_i^\star$, with $b_i^\star$ the solution of the constrained maximization program. For any pollution constraint, the abatement cost then corresponds to the foregone revenue, or $p_y \times (f_i(b_i^{LF}) - f_i(b_i^{LF} - a_i))$. The plant's m.a.c. can be computed as the derivative of the above: $p_y \times f_i'(b_i^{LF} - a_i)$.

Next, to obtain an industry m.a.c. curve mapping pollution prices against abatement efforts, first denote plant i's m.a.c. $MC_i(a_i) = p_y \times f_i'(b_i^{LF} - a_i)$ to obtain $a_i = b_i^{LF} - (f_i'^{-1})(MC_i/p_y)$. The last expression gives, for plant i, the quantity of emissions reduced relative to baseline emissions at any implicit pollution price. At the industry level I, the total abatement effort at any price then corresponds to the horizontal sum of a over plants:

$$a_I = \sum_{i \in I} \left(b_i^{LF} - f_i'^{-1}(MC_i(a_i)/p_y) \right)$$

Figure 3.2.3 illustrates the correspondence between technological frontiers and m.a.c. curves. Although plants can experience some technical inefficiency in practice, revenue maximization necessarily results in technically efficient production decisions. In turn, m.a.c. are computed along the technological frontier, meaning that zero-cost abatement measures are non-existent.

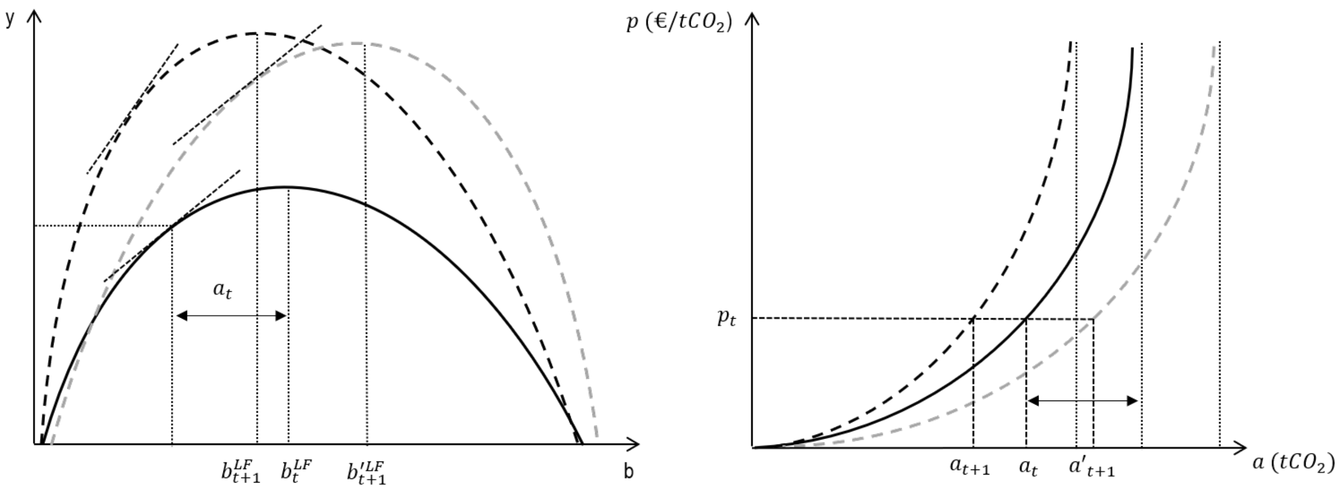
The left part of Figure 3.2.3 illustrates an industry's technological frontier $f(b)$ before technological progress occurs (plain black line). Starting from baseline emissions b_t^{LF}, any level of pollution constraint matches an implicit price of pollution. Graphically, and for an arbitrary abatement effort a_t, the corresponding m.a.c. reflects the absolute value of the slope of the tangent to the technological frontier. Besides, the asymptote of m.a.c. curves shown in Figure 3.2.3 corresponds to the maximum abatement that can be done at the industry level. Note indeed that $laisser faire$ conditions correspond to the intercept of the m.a.c. curve. Then, as pollution control strengthens, the foregone revenue from production increases and tends to infinity as emissions tend to zero.

It becomes clear in Figure 3.2.3 that the shape of m.a.c. curves is inherently linked to that of technological frontiers, and the nature of technological progress in turn. Specifically, *non-directed* and *weakly directed* technological progress shifts the m.a.c. 's asymptote to the right as baseline emissions increase, which will result in lowering the m.a.c. curve (dashed grey line). By contrast, *strongly directed* technological progress shift the asymptote to the left, which contributes to increasing m.a.c. (dashed black line). Changes in the curvature of the technological frontier due to technological progress will also affect the slope of m.a.c. curve, in no clear direction yet.

3.3 Empirical Approach

In this Section, we apply our theoretical framework to manufacturing industries covered under the EU-ETS during the early third trading period (2013-17), and analyze the effect of technological progress on industries' m.a.c. curves.

FIGURE 3.2.3: Technological change and m.a.c. curves



3.3.1 Data

First, we collect input, production and pollution data at the plant level to estimate industries' technological frontiers, conforming to the theoretical framework presented in section 3.2. Two databases, paired by plant names (*"account holder name"*) are used. First, the Amadeus database from Bureau van Dijk documents financial information on European production sites, including annual accounts, financial ratios, industry and ownership. Amadeus data covers the 2009-2017 period. Second, the European Union Transaction Log (EUTL) records the trading and compliance activity of plants covered under the EU-ETS, including transactions, annual allocation and reconciliation of permits. The EUTL covers the same years as Amadeus, yet the transition from the second (2008-2012) to third (2013-2020) trading period led to discrepancies in the reporting of emissions data, as many production sites changed account holder name. Therefore, we choose 2013 as the initial date for our panels, which coincides with the start of Phase 3 of the EU-ETS. We obtain balanced panels binned in seven 4-digit NACE rev. 2 code,[5] from 2013 to 2017. Table 3.3.1 provides an overview of selected industries, most of which are manufacturing of mineral products and basic metals, plus the power sector.

Using the practical guidance of Coelli et al., 2005, we select capital, labor and energy as inputs, and production and CO_2 emissions as desirable and undesirable outputs. More precisely, capital is measured by the value of tangible assets, labor by total payroll and energy by the value of purchased raw materials and other supplies. Production is measured by sales revenues and pollution by verified CO_2 emissions. Besides, to correct inflation variations over-time and price-level differences across countries, we deflate the

[5]We chose to merge NACE 20.12, 20.13 and 20.14 under a more general «Chemicals» industry, due to data scarcity at the 4-digit level. We checked that three sub-industries present similar carbon intensities.

TABLE 3.3.1: Industry description

Industry	NACE rev. 2	Activity description
Baked clay	23.32	Manufacture of bricks, tiles and construction products, in baked clay
Cement	23.51	Manufacture of clinkers and hydraulic cements, including Portland, aluminous cement, slag cement and superphosphate cements
Chemicals	20.1(2-3-4)	Manufacture of organic and inorganic basic chemicals, dyes and pigments
Electricity	35.11	Production of electricity, including operation of generation facilities that produce electric energy
Metallurgy	24.1	Manufacture of basic iron and steel and of ferro-alloys
Paper	17.12	Manufacture of paper and paperboard
Plaster	23.52	Manufacture of plasters of calcined gypsum or calcined sulphate, and manufacture of quicklime, slacked lime and hydraulic lime

data with an inflation index and convert it to purchasing power parity.[6] Table 3.3.2 reports descriptive statistics of the resulting samples, and Figure 3.7.1 in the appendix shows the dynamics of variables over 2013-17. Note that data belonging to a NACE 4-digit industry can be split in two or three sub-samples according to carbon intensity, measured by the average emissions-to-production ratio of plants over all years (see for instance baked clay products, metallurgy and paper production). This first ensures that samples have a similar 20-to-30 observations. Having homogeneous samples, in terms of economic activity, is indeed a central point of the technological frontier calibration presented in Section 3.3.2. Second, it enables us to further analyze whether the carbon intensity of production affects the nature of technological progress.

On average for the selected production sites, Table 3.3.2 shows that cement and power sectors are the biggest emitters, with more than 400ktCO_2 annually. Manufacturers of mineral product (NACE 23) also have the highest carbon intensity.[7] Moreover, computing the capital intensity of production sites, i.e. the capital-to-production ratio, reveals that on average, plants that have a higher carbon intensity of production also tend to be more capital intensive.[8] We could therefore expect a greater potential for *directed* technological progress in those industries. Surprisingly, cement manufacturers presents a low capital intensity despite being highly carbon intensive. This could be due to the use of

[6]https://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do

[7]Recall that carbon intensity is usually expressed in tCO_2/unit of production, yet it is expressed in tCO_2/k€ in our case, as our data is in constant € corrected with purchasing power parity.

[8]Capital intensity is lower than one in most cases, meaning that the value of production is superior to that of tangible assets on average.

carbon inputs, which is not reflected here, or a low valuation of tangible assets.

TABLE 3.3.2: Data overview

Industry (Nace 2)	#Obs	Carbon intensity	Capital intensity	Emissions	Production	Capital	Energy	Labor
Baked clay (23.32)	28	0.4 (0.7)	0.6 (0.7)	18,035 (14,541)	42,437 (20,536)	26,762 (14,370)	15,342 (5,765)	10,376 (3,733)
	29	3.6 (4.1)	1.2 (0.7)	11,082 (7,756)	3,012 (1,886)	3,541 (1,467)	1,198 (670)	638 (442)
Cement (23.51)	26	5.1 (6.8)	0.6 (0.7)	626,319 (56,794)	121,636 (83,456)	75,303 (62,588)	38,167 (29,623)	22,268 (13,580)
Chemicals (20.1)	20	0.3 (0.4)	0.3 (0.3)	156,674 (87,645)	578,601 (195,624)	160,064 (78,383)	328,671 (73,810)	60,224 (19,944)
Electricity (35.11)	22	1.1 (0.2)	0.9 (1.2)	420,341 (49,204)	379,998 (229,560)	356,290 (269,279)	200,814 (116,953)	37,284 (18,726)
Metallurgy (24.1)	28	0.1 (0.1)	0.2 (0.2)	68,845 (54,413)	574,689 (420,228)	138,704 (95,780)	395,098 (281,465)	55,397 (40,344)
	25	0.5 (0.6)	0.4 (0.4)	116,663 (91,921)	232,382 (134,096)	78,202 (49,529)	148,902 (75,231)	22,532 (15,432)
Paper (17.12)	25	0.1 (0.1)	0.2 (0.2)	18,659 (12,863)	138,541 (109,382)	33,715 (26,437)	69,946 (50,405)	19,988 (14,778)
	24	0.5 (0.4)	0.2 (0.9)	49,887 (26,564)	104,520 (69,471)	24,191 (20,540)	64,404 (31,181)	12,816 (7,639)
	25	1.1 (0.9)	0.3 (0.4)	69,714 (44,097)	63,828 (47,870)	22,034 (17,566)	33,898 (23,029)	7,392 (4,826)
Plaster (23.52)	27	2.8 (4.6)	0.7 (0.5)	122,911 (81,940)	43,651 (17,475)	32,705 (8,425)	14,396 (4,662)	6,716 (2,352)

Note: Indicated values are means over years and plants. Production and inputs are expressed in k€. Emissions are expressed in tCO_2. The column #Obs indicates the number of production sites per cross-section. Medians are reported in brackets.

3.3.2 Directional distance functions

Next, we employ a directional distance function (d.d.f.) approach to calibrate industries' technological frontiers over the 2013-17 period. First introduced by Chung, Färe, and Grosskopf, 1997, the general idea behind d.d.f. is to minimize the distance between observed plants and their technological frontier. It is then possible to identify plants that are technically efficient (namely, make the most of inputs given the state of technology) and those for which technical efficiency improvements are possible. As such, d.d.f. has been widely used as a management tool to benchmark decision-making-units (e.g. companies' services, production plants etc.). This approach has several methodological advantages. First, it does not require any assumption about the economic or regulatory environment (Wei, Löschel, and Liu, 2013; Zhou, Zhou, and Fan, 2014). Second, data requirements are modest in d.d.f. analysis (only input and output quantities or values are needed at the production unit level), which facilitates its implementation and reproduction. Therefore, the d.d.f. method has allowed to develop a measure of technical efficiency and total factor productivity growth that does not rely on the price of production factors.

Formally, an individual directional distance function is defined as[9]

$$\vec{D}_i(x, y, b; g_y, -g_b) = \sup\{\beta : (y + \beta g_y, b - \beta g_b) \in P(x)\} \tag{3.3.1}$$

where β represents the maximum expansion (resp. contraction) in the good (resp. bad) outputs allowed by the plants' technological state along some direction vector $g = (g_y, -g_b)$. Graphically, the directional distance function projects each decision-making-unit onto the boundary of the production set (or frontier). The inefficiency score β is then null for technically efficient plants, which lie on the technological frontier, while plants for which technical efficiency improvements are possible present a positive distance.

For the purpose of this study, the specification of the d.d.f. must fulfill two criteria. First, it must be parametric since we need a technological frontier that is twice differentiable for our analysis of marginal abatement cost curves. We then exclude the Data Envelopment Analysis method, which consists in evaluating plants' technical efficiency scores β with a non-parametric approach, for it would result in a piece-wise representation of m.a.c. curves. Second, the d.d.f. 's functional form must allow for linear transformation of parameters, to satisfy the translation property (Färe et al., 2005). This translation property ensures the distance from a plant's good and bad output bundle to the technological frontier is minimized along the chosen direction vector. It reads

$$\vec{D}_i(x, y, b; g_y, -g_b) = \vec{D}_i(x, y + s \times g_y, b - s \times g_b; g_y, -g_b) + s \tag{3.3.2}$$

with s a scalar. The translation property excludes logarithmic specifications in turn, despite trans-log forms often being used in general output distance functions frameworks. Instead, we choose a quadratic distance function as in Färe et al., 2005 and Wei, Löschel, and Liu, 2013. With $k = 3$ inputs $x_{k,t}$ (capital, labor and energy), one desirable output y_t

[9] The i subscript on inputs and outputs have been omitted for simplicity.

(sales revenue) and one pollutant b_t (CO_2 emissions), the d.d.f. reads

$$D_{i,t}(x_{k,t}, y_t, b_t) = \alpha_0 + \sum_{k=1}^{3} \alpha_k x_{k,i,t} + \beta_1 y_{i,t} + \gamma_1 b_{i,t} + \frac{1}{2}\sum_{k=1}^{3}\sum_{k'=1}^{3} \alpha_{kk'} x_{k,i,t} x_{k',i,t} + \frac{1}{2}\beta_2 y_{i,t}^2 + \frac{1}{2}\gamma_2 b_{i,t}^2 + \sum_{k=1}^{3} \delta_k x_{k,i,t} y_{i,t} + \sum_{k=1}^{3} \eta_n x_{k,i,t} b_{i,t} + \mu y_{i,t} b_{i,t} \tag{3.3.3}$$

We choose the direction vector $g = (1, -1)$, which corresponds to a simultaneous expansion of production and contraction of pollution, as is standard in the related literature on shadow price estimation (Färe, Grosskopf, and Weber, 2006; Marklund and Samakovlis, 2007; Zhou, Fan, and Zhou, 2015; Wei, Löschel, and Liu, 2013).[10] Moreover, imposing the translation property to the quadratic specification requires the following parameter restrictions: (i) $\gamma_1 = \beta_1 + 1$, (ii) $\beta_2 = \gamma_2 = \mu_2$, (iii) $\delta_n = \eta_n$ and (iv) $\alpha_{nn'} = \alpha_{n'n}$.

The model then becomes

$$D_{i,t}(x_{i,k,t}, y_{i,t}, b_{i,t}) = \alpha_0 + \sum_{k=1}^{3} \alpha_k x_{k,i,t} + \beta_1 (y_{i,t} + b_{i,t}) + \frac{1}{2}\sum_{k=1}^{3}\sum_{k'=1}^{3} \alpha_{kk'} x_{k,i,t} x_{k',i,t} + \frac{1}{2}\beta_2 (y_{i,t} + b_{i,t})^2 + \sum_{k=1}^{3} \delta_k x_{k,i,t} (y_{i,t} + b_{i,t}) + b_{i,t} \tag{3.3.4}$$

which we calibrate below.

3.3.3 Frontier calibration

Next, we calibrate the parameters of equation 3.3.4, using a deterministic, linear programming method. Two reasons moved us away from an econometric estimation (or stochastic frontier analysis). First, it does not accommodate small sample sizes, yet we use data with a fine granularity to ensure comparability between production sites' activities. Besides, working at a dis-aggregated level enables us to analyze the effect of technological progress across sectors. Second, stochastic frontier analysis usually relies on maximum likelihood estimation (Murty, Kumar, and Dhavala, 2007; Behr, 2015; Löschel, Lutz, and Managi, 2019), which results are highly dependent on the assumptions about the distribution of errors. By contrast, the deterministic approach directly reveals the state of technology from the data, without other assumptions than the functional form of the technological frontier.

[10] A sensitivity analysis of direction vectors can be found in Vardanyan and Noh, 2006.

As in Färe et al., 2005 and Wei, Löschel, and Liu, 2013, we calibrate industries' technological frontiers using the following linear-quadratic program $\mathcal{P}$:

$$\begin{aligned}
&Min\ \left[\vec{D}_{i,t}(x_{i,k,t}, y_{i,t}, b_{i,t}; g)\right] \quad \text{such that} \\
&\text{(a)} \quad \vec{D}_{i,t}(x_{i,k,t}, y_{i,t}, b_{i,t}; g) \geq 0 \\
&\text{(b)} \quad \partial\vec{D}_{i,t}/\partial y_{i,t} \leq 0 \\
&\text{(c)} \quad \partial\vec{D}_{i,t}/\partial b_{i,t} \geq 0 \\
&\text{(d)} \quad \partial\vec{D}_{i,t}/\partial x_{i,t} \geq 0 \\
&\text{(e)} \quad \vec{D}_{i,t}(x_{i,k,t}, 0, 0; g) < 0
\end{aligned}$$

Where $\vec{D}_{i,t}(x_{i,k,t}, y_{i,t}, b_{i,t}; g)$ is defined as in equation 3.3.4. Importantly, minimizing the distance removes any technical inefficiency, as plants are projected onto the technological frontier in the (b, y) space. In turn, $\hat{D}_{i,t}(x_{k,t}, y_t, b_t; g) = 0$ implicitly defines an expression for the technological frontier. Moreover, the program's constraints ensure that the production possibility set has the desired shape. In particular,

- (a) implies that observations are located on or under the technological frontier
- (b) and (c) imply that the distance to the frontier decreases (resp. increases) with respect to a marginal increase in the good (resp. bad) output
- (d) implies that inefficiency increases with input use
- (e) states that a positive amount of inputs must be associated with some production

Besides, $\mathcal{P}$ allows CO_2 emissions b to be positive with a null production, $y = 0$. This corresponds to residual emissions that can take place in practice, due to the preliminary heating of machinery for instance.

The linear-quadratic program $\mathcal{P}$ is run on industries' sequential production possibility sets, namely using observations from the initial date up to time t (Oh and Heshmati, 2010). For instance, 2014's frontier is obtained by calibrating the distance function on 2013 and 2014 observations, while 2015's frontier relies on 2013, 2014 and 2015 data (and so forth until 2017).[11] This approach enables us to take into account that a technologically feasible production set remains valid in the future. Thus, it implies that over time, technological progress can only push the technological frontier upwards. Moreover, and by contrast to a contemporaneous production set which only contains t-time observations, the sequential set embodies any technological change occurring from the initial date up until the year of interest. Last, we normalize input and output data by the

[11] In turn, year t sample has $(t - 2013 + 1) \times N$ observations.

samples' means[12] to avoid convergence problems (Färe et al., 2005; Wei, Löschel, and Liu, 2013).

3.4 Results

This section first presents results from the calibration of the distance function, namely technical efficiency and technological frontier estimates across industries and over time. Next, it discusses the effect of *directed* and *non-directed* technological progress on industries' m.a.c. curves.

3.4.1 Efficiency and technological change

Once technological frontiers calibrated, we start by computing plants' zero-cost abatement potential from the estimated distance to the technological frontier (or equivalently, technical efficiency score). Distance estimates corresponds to those emissions reductions that can be achieved by improving the technical efficiency of production without changing the quantity or allocation of inputs.

Denoting $\hat{D}_{i,t}(x_t, y_t, b_t)$ the calibrated distance function, the zero-cost abatement potential of plant i at time t corresponds to $\hat{D}_{i,t} \times \bar{b}_t$, with $\bar{b}_t$ the samples' mean pollution (recall that data is normalized). Table 3.4.1 reports average (over plants and years) values as a percentage of observed emissions. Results indicate that potential emission reductions due to technical efficiency improvements are important, ranging from 20% in the chemical industry to more than 70% in electricity and paper production. The dispersion of values within each sample (standard deviations are reported in brackets) further indicates a strong heterogeneity in the data, with efficient plants operating on the technological frontier and others for which significant improvements are possible.

Furthermore, we analyze technological and efficiency changes across industries using a sequential Malmquist-Luenberger (SML) total factor productivity index. Developed by Chung, Färe, and Grosskopf, 1997, and adapted by Oh and Heshmati, 2010 in the context of sequential production sets, the SML index enables to measure the evolution of plants' productivity over time. Specifically, the index can be decomposed into two terms capturing (i) changes in technical efficiency on the left (how far observations lie from the technological frontier), and (ii) technological progress (by how much the technological

[12] The average plant is defined by the $(x_{i,k,t}, y_{i,t}, b_{i,t}) = (1, 1, 1)$ coordinates

frontier expands). The plant-level, year-to-year index can be computed as

$$SML_i^{t,t+1} = \left[\frac{D_i^t(x_t, y_t, b_t)}{D_i^t(x_{t+1}, y_{t+1}, b_{t+1})} \times \frac{D_i^{t+1}(x_t, y_t, b_t)}{D_i^{t+1}(x_{t+1}, y_{t+1}, b_{t+1})}\right]^{1/2}$$
$$= \underbrace{\frac{D_i^t(x_t, y_t, b_t)}{D_i^{t+1}(x_{t+1}, y_{t+1}, b_{t+1})}}_{\text{Efficiency change (EC)}} \times \underbrace{\left[\frac{D_i^{t+1}(x_t, y_t, b_t)}{D_i^t(x_t, y_t, b_t)} \times \frac{D_i^{t+1}(x_{t+1}, y_{t+1}, b_{t+1})}{D_i^t(x_{t+1}, y_{t+1}, b_{t+1})}\right]^{1/2}}_{\text{Technological change (TC)}}$$

To obtain the total productivity change over the period, the SML index can be chained over the years as follows

$$SML_i^{tot} = SML_i^{2013,2014} \times SML_i^{2014,2015} \times SML_i^{2015,2016} \times SML_i^{2016,2017}$$
$$= (EC_i^{2013,2014} \times EC_i^{2014,2015} \times EC_i^{2015,2016} \times EC_i^{2016,2017}) \times$$
$$(TC_i^{2013,2014} \times TC_i^{2014,2015} \times TC_i^{2015,2016} \times TC_i^{2016,2017})$$
$$= EC_i^{tot} \times TC_i^{tot}$$

Specifically, the SML_i^{tot} indicates total factor productivity gains (resp. losses) over the period when > 1 (resp. < 1), and a constant productivity when $= 1$. Because of the sequential production set approach yet, the technological change component cannot be < 1 (Oh and Heshmati, 2010). In turn, any productivity loss is due to a decrease in technical efficiency. The plant average of SML_i^{tot}, EC_i^{tot} and TC_i^{tot} are reported in Table 3.4.1.[13]

First, samples with relatively low (high) carbon intensity in 2013 tend to experience productivity losses (gains) over the period. This is the case in baked clay products manufacturing, metallurgy, paper and chemical industries, where the efficiency regression outweighs technological progress. Yet, the observed deterioration of the technical efficiency of production over time has to be nuanced. Let us indeed turn to Figure 3.4.1 which plots EC_i^{tot} against TC_i^{tot} for every observation in the metallurgy, low carbon-intensity sample. First, the majority of points lie in the upper left corner, which implies at first sight a negative correlation between technological progress and technical efficiency improvements ($TC_i^{tot} > 1$ and $EC_i^{tot} < 1$). Yet, Figure 3.4.1 also shows that a few plants have carried out important technological progress over the period, suggesting an important displacement of the technological frontier. This may partly explain the average decrease in technical efficiency observed during the period.

[13] We do not report intermediary, year-to-year indexes because no noticeable pattern stands out.

TABLE 3.4.1: Efficiency and technical change

Industry	Carbon intensity	Zero-cost abatement potential (% of observed emissions)	Decomposition of the SML index		
			$SML_i^{2013,2017}$	Eff. change	Tech. change
Baked Clay (23.32)	0.4	35% (0.17)	0.96 (0.85)	0.67 (0.31)	1.44 (0.92)
	3.6	55% (0.30)	1.25 (1.66)	0.60 (0.71)	2.8 (2.01)
Cement (23.51)	5.1	20.3% (0.13)	1.43 (2.52)	1.06 (1.37)	1.50 (1.32)
Chemicals (20.1)	0.3	56.2% (0.27)	0.78 (0.49)	0.63 (0.38)	1.49 (1.28)
Electricity (35.11)	1.1	73.2% (0.30)	1.05 (0.65)	1.12 (0.64)	1.11 (0.49)
Metallurgy (24.1)	0.1	24.2% (0.11)	0.75 (0.43)	0.68 (0.42)	1.14 (0.50)
	0.5	28.5% (0.15)	1.59 (4.01)	1.23 (2.62)	1.21 (0.47)
Paper (17.12)	0.1	71% (0.17)	0.99 (0.83)	1.08 (1.56)	1.08 (0.20)
	0.5	41% (0.22)	1.01 (0.75)	1.04 (0.30)	3.76 (2.63)
	1.1	39.5% (0.31)	1.03 (0.72)	0.27 (0.28)	5.76 (4.89)
Plaster (23.52)	2.8	27.4% (0.15)	0.94 (0.61)	0.98 (1.03)	1.22 (0.53)

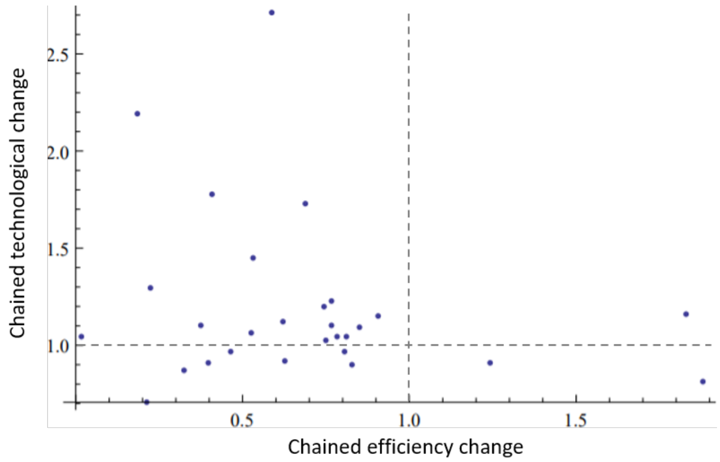
Note: Zero-cost abatement potential represents the average technical efficiency improvement over years and production sites, reported in percentage of observed emissions. Standard deviations can be found in brackets. The full SML index and its two components are meaned over observations.

Second, industries that experience productivity gains such as cement, electricity production or metallurgy (high carbon intensity sample) tend to experience technical efficiency improvements over-time. On average, the technological change component also increases with the carbon intensity of plants. This suggests that plants with a high carbon-intensity in 2013 carry out more technical and/or technological efforts than low carbon-intensity ones, which has interesting policy implications discussed in Section 3.6.

3.4.2 Effect of technological progress

Next, we compute industry marginal abatement cost curves, as outlined in section 3.2.2, and examine the effect of technological progress in the context of the EU-ETS. To do so, we keep inputs fixed at their 2013 (observed) level. This enables us to attribute year-to-year changes of m.a.c. to displacements of the technological frontier only, thereby eliminating changes due to the quantity of inputs used. Figure 3.4.2 shows the resulting

FIGURE 3.4.1: Distribution of SML index components, metallurgy (24.1)



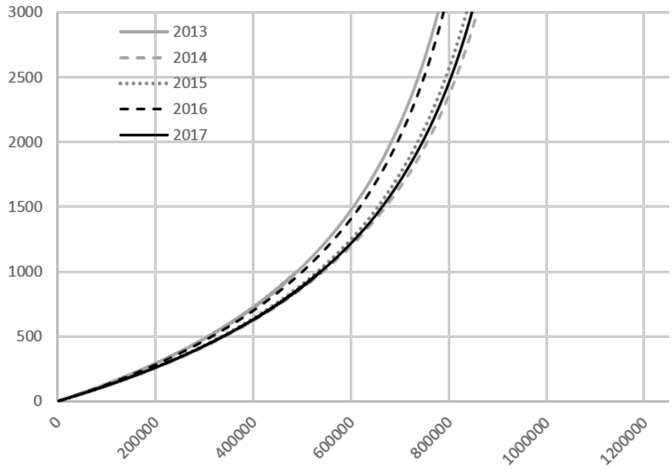
Note: Low carbon-intensity sample. The reader may have noted that the chained technological change is sometimes lower than one, although we use a sequential production set approach. This is due to imperfections in the calibration of technological frontiers, that are amplified by the multiplicative nature of the SML index.

curves in baked clay product manufacturing. As expected, they are increasing and convex, contrasting with the usual linear specification used in theoretical models of carbon markets (Chaton, Creti, and Peluchon, 2015; Chaton, Creti, and Sanin, 2018; Chevallier, 2012; Salant, 2016; Perino and Willner, 2016; Pahle et al., 2018). Moreover, their asymptotes are equal to aggregate baselines net of residual emissions. Yet, residual emissions are negligible in baked clay, and never exceed 10% of the baseline in general (see details in Table 3.8.1). Moreover, m.a.c. are substantially higher in the low carbon intensity sample. Every unit of CO_2 abated leads to a greater revenue loss when carbon intensity is low indeed.

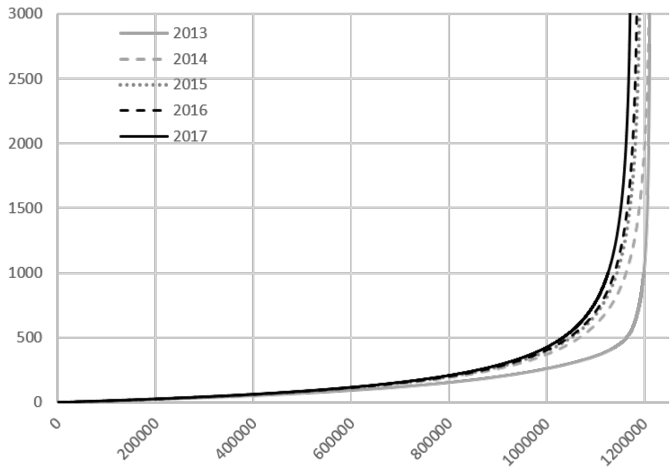
Computing abatement efforts at a price of 100€/tCO_2, which corresponds to the 2030 goal price recommended in the High-Level Commission on Carbon Prices (Stiglitz et al., 2017), reveals significant variations depending on the carbon intensity. In baked clay product manufacturing for instance, emissions reductions vary from 8% to nearly 50% between the two sub-samples (Table 3.4.2). In the context of the EU-ETS, these results suggest large permit transfers from low to high carbon intensity industries. Yet, abatement efforts at the observed European Union Allowance (EUA) prices from 2013 to 2017 are of little magnitude, ranging from 0.1% to 5.8% in dirtier plants (Table 3.4.2). This can be due to the low price levels observed over the Phase 3 of the EU-ETS (6,5€/tCO_2 on average). Besides, our results suggest a large scope for emissions reductions in the EU-ETS: at a price of 25€/tCO_2, which corresponds to the price level observed in the last few months, implied emissions reductions can reach 20% in the most carbon-intensive industries (Table 3.8.1).

FIGURE 3.4.2: Marginal abatement cost curves, baked clay (23.32)

(A) Low carbon intensity



(B) High carbon intensity



Note: The y-axis reports the marginal cost of abatement in €/tCO_2 and the x-axis reports abatement levels.

Next, we compute the percentage variation of *laisserfaire* carbon intensity over 2013-2017 to find out the type of technological progress that occurred at the industry level, conforming to the theoretical framework outlined in Section 3.2. Yearly *laisserfaire* carbon intensity is computed as $\sum_i^N b_i^{LF}/y_i^{LF}$. Results, reported in Table 3.4.2, first reveal that both *directed* (*weakly* and *strongly*) and *non-directed* technological progress occurred, depending on the industry considered. For instance, paper and baked clay manufacturers have consistently seen a decrease in *laisserfaire* carbon intensity over production, by contrast to metallurgy, which has rather experienced *non-directed* technological progress. Interestingly, technological change is rather *strongly directed* in the high carbon intensity samples (for instance, baked-clay and paper), although it is *weakly directed* in the low-carbon intensity samples. This result suggests that production sites are rather looking to improve total factor productivity when their initial carbon intensity is low, which results in an increase in baseline emissions. By contrast, production sites that are highly carbon intensive would look after low-carbon technological improvements that decrease the absolute amount of CO_2 emitted.

Consequently, the nature of technological progress affects the dynamics of m.a.c. curves. At price of 100€/tCO_2, abatement can vary by more than 50% between 2013 and 2017 due to technological change (Table 3.4.2). Specifically, *non-directed* technological progress, as in the metallurgy or plaster industries, unambiguously increases the abatement effort for a given price of CO_2. This further means that m.a.c. curves shift down over-time. By contrast, *strongly directed* technological progress results in decreasing the abatement effort between 2013 and 2017, in line with a decrease in baseline emissions (see baked clay, high carbon intensity in Table 3.4.2). Last, *weakly directed* technological progress yields greater abatement efforts for a given price, despite lowering the carbon intensity of production. Yet, note that technological progress resulted in increasing baseline emissions in most industries (i.e. was rarely *strongly directed*), thus amplifying the abatement effort at a given price.

Therefore, our results reveal that despite the environmental policy, plants do not exclusively carry out 'environmentally friendly' technological progress. This first puts into perspective the induced technological change literature, which typically focuses on low-carbon technologies. By contrast, we find that in four out of the eleven samples considered, plants carry out *non-directed* technological progress. Second, we find that technological progress can be *weakly directed*, i.e. baseline increasing, especially in industries that have a low carbon intensity in 2013. This result suggests that these plants perceive the EU-ETS as a relative constraint on emissions in practice, although it sets and absolute limit on CO_2 emissions in aggregate. By contrast, plants that have a high carbon intensity in 2013 perceive the EU-ETS as such, and carry out *strongly directed* technological progress in turn.

Finally, we use computed industry m.a.c. curves to analyze the price elasticity of pollution abatement at selected carbon price levels. Our results are consistent with that of Cialani and Mortazavi, 2018, in the context of industrial electricity demand. We first find that the elasticity of abatement demand is lower in high carbon-intensity industries. This may seem counter-intuitive, although it can be explained by the magnitude of m.a.c. being lower for high carbon intensity plants, hence selected prices (10-500€/tCO_2) corresponding to the flatter part of the m.a.c. curve. Second, and consistently with the convex shape of m.a.c. curves, abatement becomes less elastic with higher price levels regardless of industries' carbon intensity. Last, we do not find that technological progress affects

TABLE 3.4.2: Summary of abatement dynamics

Industry	Carbon intensity	%Δ in c. int.	%Δ in baseline emissions	Ave. abatement, EUA prices	Ave. abatement, 100€/tCO$_2$	%Δ in abatement, 100€/tCO$_2$
Baked clay	0.4	-4.5%	+10.6%	0.5%	8.1%	+10.4%
	3.6	-47.5%	-4.8%	4.2%	48.8%	-10.9%
Cement	5.1	+16%	+45.9%	5.8%	55.7%	+57.1%
Chemicals	0.3	-25.8%	-8.5%	1.1%	13.4%	-11.3%
Electricity	1.1	-1.2%	+6%	1.3%	19%	+7.2%
Metallurgy	0.1	+4.9%	+15.7%	0.1%	2.2%	+16.7%
	0.5	+3.2%	+21.7%	0.6%	10.2%	+30.4%
Paper	0.1	-6.5%	+1.4%	0.1%	2.6%	+3.9%
	0.5	-38.4%	-7.2%	0.5%	8.1%	-13.3%
	1.1	-50.7%	-45.6%	1.2%	18.7%	-28.4
Plaster	2.8	+3.7%	+14.5%	3.2%	39.4%	+17%

Note: %Δ corresponds to the percentage change between 2013 and 2017. The average abatement realized at EUA price is expressed in % of observed emissions, with $p^{EUA}_{2013} = 4€/tCO_2$, $p^{EUA}_{2014} = 5.1€/tCO_2$, $p^{EUA}_{2015} = 7.4€/tCO_2$, $p^{EUA}_{2016} = 6€/tCO_2$, $p^{EUA}_{2017} = 6.7€/tCO_2$.

the price elasticity of abatement over time. This result confirms that m.a.c. dynamics are mainly driven by variations in baseline emissions, rather than changes in the curvature of the technological frontier.

TABLE 3.4.3: Elasticity of emissions abatement

Industry	Carbon Intensity	Price elasticities				
		10€/tCO$_2$	25€/tCO$_2$	50€/tCO$_2$	100€/tCO$_2$	500€/tCO$_2$
Baked clay	0.4	0.99	0.98	0.96	0.93	0.72
	3.6	0.94	0.86	0.75	0.59	0.16
Cement	5.1	0.92	0.81	0.68	0.49	0.08
Chemicals	0.3	0.99	0.98	0.97	0.95	0.81
Electricity	1.1	0.98	0.95	0.91	0.84	0.47
Metallurgy	0.1	0.99	0.99	0.99	0.98	0.90
	0.5	0.99	0.97	0.95	0.92	0.68
Paper	0.1	0.99	0.99	0.98	0.97	0.89
	0.5	0.99	0.98	0.96	0.92	0.70
	1.1	0.98	0.95	0.91	0.84	0.48
Plaster	2.8	0.95	0.89	0.80	0.66	0.22

3.5 Equilibrium in the carbon market

In this section, we exploit permit allocation data from the EUTL and computed m.a.c. curves to analyze the effect of technological progress on the carbon market equilibrium. This analysis should be taken as illustrative only, as our samples only account for a share of production sites covered under the EU-ETS (see Table 3.5.1).

First, we compute annual permit demand as the difference between permit allocation, which we aggregate at the industry level, and computed baseline emissions. Here, we do not consider the inter-temporal trading of permits (i.e. banking and borrowing) in order to isolate the sole effect of technological progress on market equilibrium. Table 3.8.2 reports the permit allocation, emissions baseline and the resulting permit demand in the 11 samples. Note that the electricity sector does not receive any permits for free as a result of auctions being the default allocation method starting in 2013. Interestingly, chemicals and paper sectors (medium and high carbon intensity sample) experienced a decrease in their annual permit demand over 2013-2017. This implies that the linear reduction factor, driving the decline of the legal emissions ceiling, did not compensate the large decrease of baseline emissions due to *strongly directed* technological progress (Table 3.8.2). In other sectors yet, permit demand increases over the years, as a result of baseline-inflating technological progress and the tightening of pollution control.

Second, and since our samples only represent a fraction of the EU-ETS, we introduce an autonomous demand (it can be positive or negative) which represents the rest of the market. More precisely, the autonomous demand is calibrated to eliminate differences between the computed equilibrium price and observed EUA price in the initial year (2013). Kept constant thereafter, this enables us to attribute the difference between average observed EUA prices and computed prices to technological progress.

Besides, we compute permit supply as the total abatement realized for a given pollution price, namely the horizontal sum of industries' marginal abatement cost curves (Section 3.2.2). The market clearing price then equalizes permit demand, i.e. total baseline emissions plus the autonomous demand, to the market permit supply, which is driven by the permit price according to m.a.c. curves. Next, we can compute net permit demand at the industry level, at the computed clearing price. This enables us to analyze industries' net position in the market, namely the difference between permit demand (as baseline emissions minus free allocation) and realized abatement at the market clearing price. Table 3.5.1 reports the results.

First, and looking at net permit demands in equilibrium (Table 3.5.1), we find that all industries are permit buyers. This is due to the autonomous demand which is negative, thus adding up to the permit supply. It further means that the market equilibrium using our sample data alone would have resulted in a much higher clearing price than that observed in 2013 in the EU-ETS. This can be due to the large permit bank that was accumulated over the second trading period, and that we do not take into account here, or the small proportion of plants in notoriously over-allocated sectors such as chemicals and metallurgy (samples' share of emissions in the entire sector is reported in Table 3.5.1). Furthermore, higher carbon-intensity industries tend to hold a shorter position than low carbon ones. Intuitively, this implies that dirtier plants need to buy more allowances in the market than cleaner ones to cover their emissions. In turn, higher carbon-intensity plants bear the financial burden of permit purchases, which tends to be amplified by the price increase due to *non-directed* technological progress.

Second, we find that technological progress has an upward effect on annual equilibrium prices. Specifically, the computed price starts at the same level as the average EUA price in 2013, namely 4€/tCO_2, as a result of the calibrated autonomous demand. Thereafter, the clearing price exceeds the EUA by approximately 2€/tCO_2 in 2014 to 38.4€/tCO_2 in 2017. Technological progress has a *weakly directed* or *non-directed* nature in most samples indeed. This results in an aggregate inflation of baseline emissions over the period, increasing the market permit demand in turn. Yet, our results suggest that *strongly directed* technological progress can be an instrument to alleviate compliance costs. In the paper industry for instance (high carbon intensity samples), technological progress alleviates the net permit demand by more than 2 mtCO_2.

3.6 Policy Implications

In the context of the EU-ETS, we first find that *non-directed* technological change is at least as, if not more prevalent than *directed* technological progress for regulated, manufacturing plants. It implies that in presence of an environmental regulation, plants primarily seek total factor productivity gains, which can have repercussions on the outcomes of the policy. Furthermore, technological change often leads to increase baseline emissions, despite decreasing the carbon intensity of production. In our context of plants covered under the EU-ETS, this results in inflating the permit price, which affects the cost effectiveness of the regulation (section 3.5). The financial burden of regulated plants is indeed amplified through two channels: (i) a shorter market position and (ii) a dearer permit price. As a consequence, we find that only *strongly directed* technological progress enables to alleviate plants' compliance costs.

Interestingly, these results suggest that plants often perceive the EU-ETS as a relative cap on emissions in practice, namely a carbon intensity target, rather than an absolute limit on emissions, which it actually is. This is particularly salient when plants have

TABLE 3.5.1: Market equilibrium

Industry	Emissions share	Carbon intensity	Net demand ($mtCO_2$)				
			2013	2014	2015	2016	2017
Baked Clay (23.32)	14.2%	0.4	0.388	0.507	0.499	0.415	0.504
		3.6	0.676	0.698	0.619	0.437	0.438
Cement (23.51)	14.1%	5.1	11.318	12.159	11.596	11.819	13.561
Chemicals (20.1)	4.8%	0.3	6.779	5.579	6.132	6.154	6.225
Electricity (35.11)	1,2%	1.1	32.733	33.752	33.203	31.894	31.745
Metallurgy (24.1)	3.1%	0.1	1.934	1.988	2.358	2.582	2.642
		0.5	2.483	2.900	3.557	4.144	3.533
Paper (17.12)	13.9%	0.1	0.389	0.647	0.643	0.640	0.515
		0.5	0.988	0.897	0.952	0.976	0.886
		0.9	5.221	3.452	2.916	4.224	3.071
Plaster (23.52)	12.4%	2.8	3.301	3.643	3.739	2.927	3.085
Clearing price (€/tCO_2)			4	7	19.9	44.2	45.1
EUA price (€/tCO_2)			4	5.1	7.4	6	6.7
Price gap (€/tCO_2)			0	+1.9	+12.5	+38.2	+38.4

Note: Note that the aggregate annual net demand equals the opposite of the calibrated autonomous demand, namely $-6.6214 \times 10^7 tCO_2$. The price gap then represents the difference between observed EUA prices and the market clearing price.

a low carbon intensity in 2013. We argue that this biased perception could be due to the allowance allocation method. In 2013, an allowance distribution method based on 'benchmarking' was implemented in the EU-ETS manufacturing sector. More precisely, free allocation is determined based on product benchmarks, defined as the average of the 10% most greenhouse gas efficient installations in terms of carbon intensity of production over the years 2007-2008. Actual allocation levels are then computed by multiplying the benchmark by a historical production level and carbon leakage exposure factors. By setting a carbon-intensity standard within industries, 'dirtier' plants are incentivized to clean their production, while 'cleaner' ones receive all the permits needed to cover their emissions.[14]

For the time being, a single study assesses the impact of product benchmarks empirically (Sartor, Pallière, and Lecourt, 2014), and finds that the new allocation method reduces the scope for windfall gains by EU-ETS firms. Although this study does not conduct an impact evaluation of product benchmarks on technological adoption, our results suggest that they could contribute to homogenize plants' carbon intensity within industries. On the one hand, highly carbon intensive plants could have an incentive to

[14]Over the third (and current) trading period, a 43% share of the total permit offer is covered by a product benchmark (European Commission)

carry out *strongly directed* technological progress and reduce their baseline emissions, in order to have a longer their position on the permit market. On the other hand, low carbon intensity plants, would rather benefit from the more generous permit endowment to carry out *weakly directed* or *non-directed* technological progress, and increase their total factor productivity.

We also believe that the directional distance function approach used in this study, which is also a benchmarking method, has several methodological advantages which make it an interesting alternative to the EU-ETS benchmarking procedure. First, the development of product benchmarks was rather costly and cumbersome, as it took two years of extensive consultations and expertise with various stakeholders. By contrast, the d.d.f. analysis accommodates little input and output data at the plant level, making it possible to update technical efficiency scores and baseline emissions at little cost. Using updated historical emissions factors and benchmarks could then be very beneficial in terms of cost efficiency and effort sharing in the EU-ETS. This study points out that relying on a grandfathering allocation method underrates the effect of technological progress on the effective abatement demand, with impacts on the carbon market outcomes.

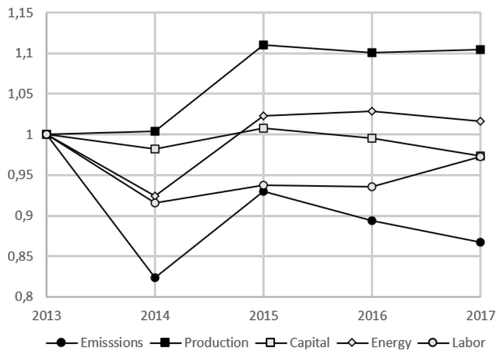
Second, the d.d.f. approach reflects plants' production process as a whole, including indirect emissions (related to energy or raw material purchase) to evaluate technical efficiency scores. By contrast, computing plants' permit allocation on the basis of their output, as is currently done in the EU-ETS, presents some shortcomings. Zipperer, Sato, and Neuhoff, 2017 raise that output-based allocation methods give an incentive to plants to outsource the production of upstream inputs to off-site facilities, in order to avoid indirect emissions being reflected in their emissions reports. By contrast, tuning plants' permit endowments on the basis of the efficiency input use, as is done in d.d.f. approaches, could bring an incentive to optimize the production lines, with greater environmental impacts.

Appendices of Chapter 3

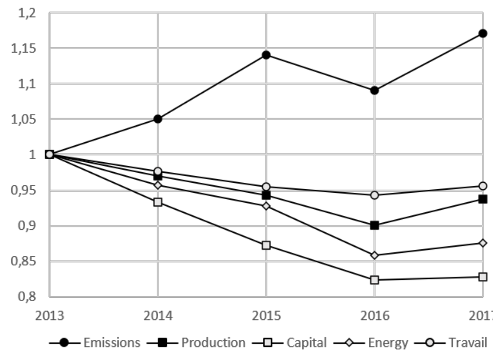
3.7 Descriptive statistics of panels

FIGURE 3.7.1: Input and output dynamics across industries

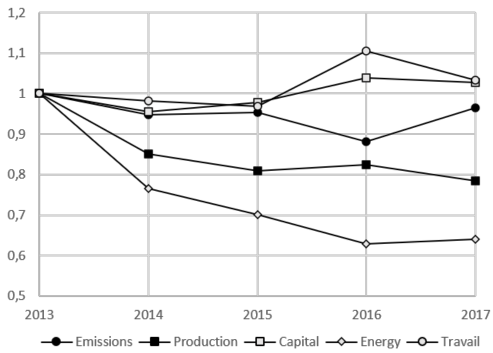
(A) Baked Clay - High c.i.



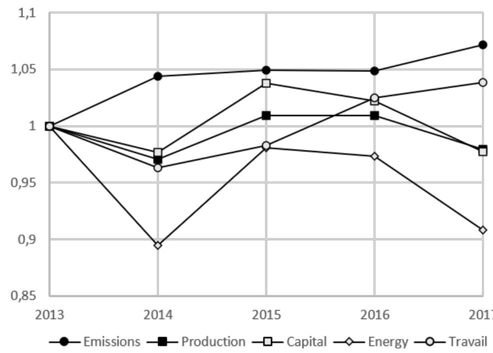
(B) Baked clay - Low c.i.



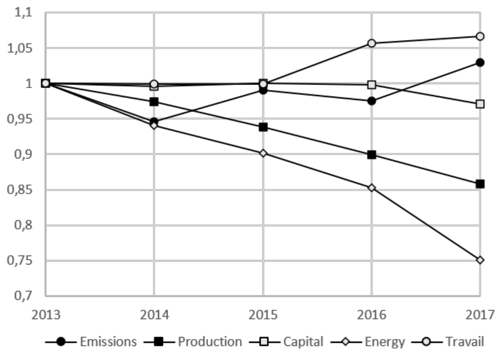
(C) Chemicals



(D) Cement



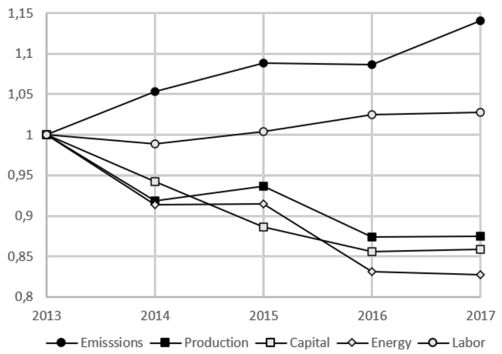
(E) Electricity



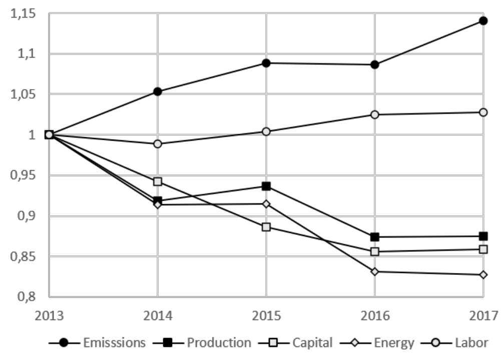
Note: c.i. refers to as carbon intensity

FIGURE 3.7.2: Input and output dynamics across industries - continued

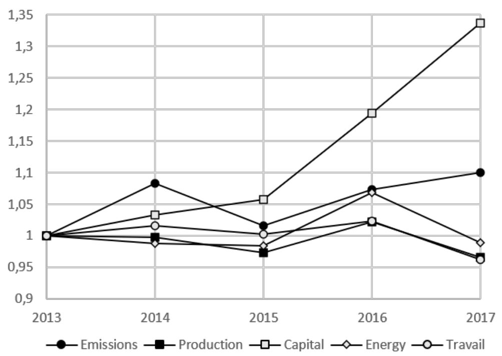
(A) Metallurgy - High c.i.



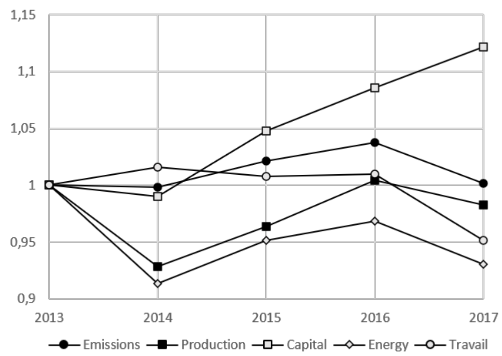
(B) Metallurgy - Low c.i.



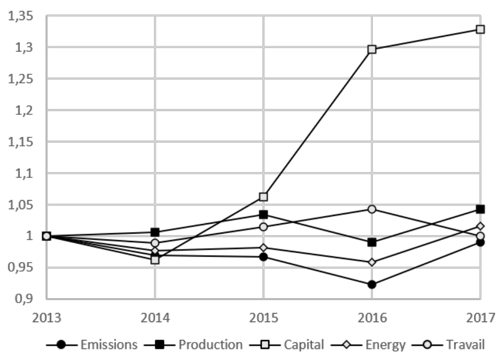
(C) Paper - Low c.i.



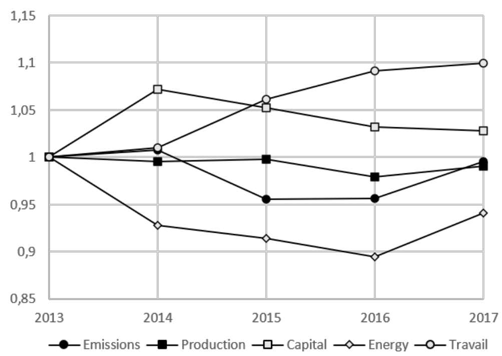
(D) Paper - Medium c.i.



(E) Paper - High c.i.



(F) Plaster



Note: c.i. refers to as carbon intensity

3.8 Detailed results

TABLE 3.8.1: Abatement dynamics: details

Industry	Carbon Intensity	Year	Baseline emissions ($mtCO_2$)	Residual emissions	Abatement EUA price	Abatement 25€/tCO_2	Abatement 100€/tCO_2	Δabatement$_{t-1,t}$, 100€/tCO_2
Baked clay	0.4	2013	0.963	1.7%	0.3%	2.1%	8%	0%
		2014	1.045	1.9%	0.4%	2.1%	8.1%	+10.8%
		2015	1.099	1.5%	0.6%	2.2%	8.2%	-2.1%
		2016	0.958	1.4%	0.5%	2.1%	8.2%	-5.8%
		2017	1.036	1.5%	0.6%	2.1%	8.2%	7.5%
	3.6	2013	1.233	1.6%	3.1	17.7%	51.1%	0%
		2014	1.216	0%	3.7%	16.1%	46.6%	-10%
		2015	1.196	0%	5.2%	16.2%	46.6%	-1.6%
		2016	1.190	0%	4.3%	16.2%	46.7%	-0.4%
		2017	1.176	0%	4.8%	16.2%	46.7%	+1.1%
Cement	5.1	2013	30.820	10.3%	3.8%	20.5%	53.8%	0%
		2014	31.153	9.5%	4.9%	20.4%	53.4%	+0.4%
		2015	34.211	7.6%	7.1%	21.1%	55.2%	+13.5%
		2016	44.677	4.8%	6.1%	22.2%	58.2%	+37.4%
		2017	44.988	4.1%	6.9%	22.3%	58.6%	+5.8%
Chemicals	0.3	2013	10.920	0.05%	0.6%	3.6%	11.3%	0%
		2014	9.663	0.8%	0.8%	3.8%	11.8%	-15.8%
		2015	9.894	0.1%	1.3%	4.1%	12.6%	+3.2%
		2016	9.980	0.02%	1.4%	5.2%	15.3%	+1.2%
		2017	9.987	0.03%	1.6%	5.4%	15.8%	+0.1%
Electricity	1.1	2013	33.022	0.8%	0.9%	5.3%	18.7%	0%
		2014	34.276	0.4%	1.1%	5.3%	18.9%	+4.4%
		2015	34.883	0.1%	1.6%	5.3%	19%	+1.8%
		2016	35.108	0.05%	1.3%	5.3%	19%	+1.3%
		2017	35.009	0.1%	1.5%	5.3%	19%	-0.3%

Industry	Carbon Intensity	Year	Baseline emissions ($mtCO_2$)	Residual emissions	Abatement EUA price	Abatement 25€/tCO_2	Abatement 100€/tCO_2	Δabatement$_{t-1,t}$, 100€/tCO_2
Metallurgy	0.1	2013	3.873	8.1%	0.1%	0.6%	2.2%	0%
		2014	3.888	8.4%	0.1%	0.5%	2.2%	-0.4%
		2015	4.232	8.6%	0.2%	0.5%	2.2%	+9.3%
		2016	4.436	6.9%	0.1%	0.6%	2.2%	+6.9%
		2017	4.481	6.9%	0.1%	0.6%	2.2%	+0.95%
	0.5	2013	5.208	11.8%	0.4%	2.5%	9.5%	0%
		2014	5.594	9.9%	0.5%	2.6%	9.7%	+9.8%
		2015	6.299	4.7%	0.8%	2.7%	10.3%	+19.7%
		2016	7.037	3.6%	0.6%	2.8%	10.5%	+13.4%
		2017	6.338	6.6%	0.7%	2.7%	10.2%	-12.5%
Paper	0.1	2013	1.274	1.7%	0.1%	0.6%	2.6%	0%
		2014	1.456	1%	0.1%	0.7%	2.6%	+15.1%
		2015	1.442	1%	0.2%	0.7%	2.6%	-1%
		2016	1.433	1.1%	0.1%	0.7%	2.6%	-0.6%
		2017	1.292	0.8%	0.2%	0.7%	2.6%	-9.6%
	0.5	2013	2.637	9.3%	0.4%	2.2%	8.5%	0%
		2014	2.522	10.1%	0.4%	2.1%	8%	-10.6%
		2015	2.526	9.9%	0.6%	2.1%	8%	+0.4%
		2016	2.574	8.2%	0.5%	2.1%	8.2%	+3.8%
		2017	2.448	10.2%	0.6%	2.1%	8%	-6.9%
	1.1	2013	6.745	1.4%	0.9%	5.6%	20.1%	0%
		2014	4.960	6.2%	1.1%	5.2%	18.4%	-32.5%
		2015	4.491	4.2%	1.5%	5%	18%	-11.5%
		2016	6.141	0%	1.3%	5.2%	18.7%	+42.2%
		2017	4.631	2.7%	1.4%	5.1%	18.2%	-26.6%
Plaster	2.9	2013	6.984	6.5%	2.2%	12.7%	39.2%	0%
		2014	7.419	6%	2.8%	12.6%	38.7%	+6.7%
		2015	7.972	4.1%	4.1%	12.8%	39.4%	+9.7%
		2016	7.974	4%	3.3%	12.8%	39.4%	+0.1%
		2017	7.997	3.8%	3.7%	12.8%	39.4%	+0.5%

Note: Residual emissions are reported as a percentage of the total baseline. The Malmquist index measures the percentage increase in the technological frontier relative to the previous year, at $b = x\%$ of baseline emissions. Average annual EUA prices are: $p_{2013}^{EUA} = 4e/tCO_2$, $p_{2014}^{EUA} = 5.1e/tCO_2$, $p_{2015}^{EUA} = 7.4e/tCO_2$, $p_{2016}^{EUA} = 6e/tCO_2$, $p_{2017}^{EUA} = 6.7e/tCO_2$. Abatement is expressed as a percentage of annual observed emissions.

TABLE 3.8.2: Abatement demand ($mtCO_2$) - details

	Industry	Baked Clay		Cement	Chemicals	Electricity	Metallurgy		Paper			Plaster
		0.4	3.6				0.1	0.5	0.1	0.5	0.9	
2013	Baseline	0.963	1.233	30.820	10.920	33.021	3.873	5.208	1.274	2.637	6.745	6.984
	Allocation	0.571	0.518	18.328	4.116	0	1.936	2.704	0.884	1.639	1.460	3.528
	Demand	0.391	0.715	12.492	6.804	33.021	1.1937	2.504	0.390	0.998	5.284	3.456
2014	Baseline	1.045	1.216	31.153	9.663	34.276	3.883	5.594	1.456	2.522	4.960	7.419
	Allocation	0.531	0.457	16.975	4.047	0	1.889	2.652	0.805	1.609	1.434	3.494
	Demand	0.513	0.758	14.177	5.616	34.276	1.994	2.941	0.650	0.912	3.525	3.924
2015	Baseline	1.009	1.196	34.211	9.894	34.688	4.232	6.299	1.442	2.526	4.491	7.972
	Allocation	0.493	0.418	16.671	3.655	0	1.855	2.603	0.790	1.531	1.393	3.404
	Demand	0.516	0.777	17.539	6.239	34.688	2.377	3.695	0.651	0.994	3.098	4.567
2016	Baseline	0.958	1.190	44.677	9.980	35.107	4.436	7.037	1.433	2.574	6.141	7.974
	Allocation	0.506	0.442	17.362	3.587	0	1.809	2.552	0.776	1.501	1.364	3.368
	Demand	0.451	0.747	27.315	6.392	35.107	2.627	4.485	0.657	1.073	4.777	4.605
2017	Baseline	1.035	1.177	46.930	9.987	35.008	4.481	6.338	1.292	2.448	4.631	7.997
	Allocation	0.492	0.426	16.723	3.159	0	1.792	2.500	0.761	1.470	1.147	3.199
	Demand	0.543	0.750	30.207	6.468	35.008	2.688	3.837	0.530	0.978	3.484	4.797

Chapter 4

Carbon price floor design in the EU-ETS power sector

This chapter is the result of a collaboration with Michael Pahle and Samuel Jovan Okullo

* * *

4.1 Introduction

It has been widely agreed that prices delivered by the EU-ETS in its second and early third trading period were too low and volatile to trigger necessary investments in the low carbon economy, and secure long-run greenhouse-gas-emissions abatement targets (Edenhofer et al., 2017). Consequently, the design of Europe's chief instrument to combat climate change was revised in February 2018 to restore the short-run scarcity of pollution permits, and and fix its supply-side rigidity. Price outcomes were largely attributed to a permit supply imbalance indeed (Grosjean et al., 2016; Ellerman, Valero, and Zaklan, 2015). Phase IV (2021-30) reform thus included an acceleration of the annual emissions cap's decline or linear reduction factor (LRF), but more importantly, equipped the EU-ETS with a quasi-automatic stabilizer referred to as the market stability reserve (MSR).

Operational in January 2019, the MSR was designed consistently with the quantity nature of the EU-ETS. More precisely, it allows to dynamically adjust annual auction volumes with respect to previous years' total number of allowances in circulation (TNAC), i.e. unused permits. For instance, the MSR tightens (relaxes) the pollution constraint when the TNAC exceeds (falls short of) a pre-defined upper (lower) threshold. Moreover, a cancellation mechanism, appended to the MSR, permanently erases allowances when the reserve becomes too large, making the effective emissions cap endogenous. In 2019, the MSR successfully cut 24% of the existing allowance surplus from auction (Marcu et al., 2020), as nearly 397 million allowances were placed in the reserve. According to *ex-ante* simulations of the EU-ETS, the cancellation mechanism could also lower the cap from 1.7 to 13GtCO_2 (Osorio et al., 2020).

Despite their successful implementation, doubts have been raised about the adequacy of the MSR and its cancellation mechanism to support and stabilize carbon prices in the EU-ETS. Four sources of concern, developed in Section 4.2, have been put forward by the literature indeed. First, there is no empirical evidence for a relationship between the quantity of allowances in circulation and carbon prices in the european carbon market (Edenhofer et al., 2017), questioning the very nature of the reform. Second, there is a sensible lag between the annual TNAC reporting and intervention by the MSR (Knopf et al., 2014), which impairs the relevance of its action. Third, the cancellation mechanism could put the market at risk of an increased price volatility, since it disturbs firms' dynamic planning (Kollenberg and Taschini, 2019). Finally, the MSR may not be able to face and absorb future sources of large-scale supply imbalances such as coal phase-outs (Flachsland et al., 2020).

To address these concerns, complementing the EU-ETS with a price floor at around 25-30€/tCO_2 has been proposed by many scholars and policy makers. The literature highlights many advantages associated with hybrid schemes indeed. From a policy perspective, a price floor could reinforce the credibility of EU's climate policy and lock revenues from auctions for member states. Besides, it would reduce the uncertainty firms face when planning their investments projects and prevent myopic price formation by explicitly signalling the target cost of carbon (Flachsland et al., 2020; Edenhofer et al., 2017). In practice, firms' planning horizon is well below the classical infinite horizon used in cap-and-trade models indeed (Quemin and Trotignon, 2019a). In 2018, french president Macron unsuccessfully offered to pave the way with a German-French coalition, but the interest for a carbon price floor has grown back after the European Green Deal was presented. The EU-ETS is indeed to be reformed again in 2021 as part of the *MSR review*, to be tuned with the carbon neutrality target set by the deal.

In this context, this study provides new material for comparison of alternative reform options. More precisely, we analyze whether the organic functions of the MSR, namely support and stability, would be outperformed by a carbon price floor policy. We use a numerical model of emissions trading developed by Mauer, Okullo, and Pahle, 2019 and calibrated to the EU-ETS power sector, which accounts for about half of EU's emissions[1]. The model includes the MSR as defined by the official EU directive and accounts for Phase IV revisions, namely the rate of decline of the emissions ceiling and the cancellation mechanism. For our comparative analysis, we introduce three plausible carbon

[1] http://sandbag-climate.github.io

price floor policies targeting a minimum price of carbon of 30€/tCO_2 : (i) an auction reserve price as in the Regional Greenhouse Gas Initiative (RGGI) and the California cap-and-trade, (ii) a flat tax on emissions as put forward in the literature (Brink, Vollebergh, and Werf, 2016; Wood and Jotzo, 2011) and (iii) a UK-like top-up levy on emissions, also referred to as carbon price support mechanism.

Therefore, this paper contributes to the *hybrid scheme* literature initiated by Roberts and Spence, 1976, and developed in Section 4.2. While a first set of deterministic simulations enables us to investigate how instruments achieve a minimum price of carbon, we also introduce demand uncertainty to test the price and support functions of three price floor policies relative to the *status quo*. Besides, and by contrast to previous studies evaluating the performance of the MSR or price-support policies, we consider the development of power-generation capacity, which can be based on fossil or renewable energy sources. Investment decisions are particularly relevant in electricity production indeed, for their important *lock-in* effect : the life expectancy of the majority of low-carbon electricity generating technologies range from 25 to 60 years (Hache et al., 2020). Therefore, our study also contributes to better understand the relationship between permit banking and low-carbon investment decisions under uncertainty, tackled analytically by Pommeret and Schubert, 2018 and Baldursson and Fehr, 2004.

The remainder is structured as follows. Section 4.2 provides an overview of the relevant strands of the literature and challenges faced by the current MSR. Next, section 4.3 presents the numerical model and equilibrium dynamics, and Section 4.4 describes the design and implementation of three policy scenarios. Section 4.5 presents the results in both deterministic and stochastic setting. Finally, Section 4.6 concludes.

4.2 Background

Hybrid schemes. In a seminal work, Weitzman, 1974 first showed that equivalent price and quantity controls in a deterministic environment will results in divergent welfare outcomes when abatement costs are uncertain. For this reason, Roberts and Spence, 1976 suggested that hybrid schemes, namely ETS complemented with a price support mechanism (single price floor or price collar), can be interesting in practice. Hybrid schemes operate like quantity controls within the range of acceptable prices indeed, providing an efficient allocation of abatement efforts. Yet, if abatement costs turn out higher or lower than expected, the price instrument takes over and transforms the hybrid scheme in a pure taxation system. Therefore, the price floor prevents under-shooting the climate target while the price ceiling, if any, avoids losing control of abatement costs, hence the cost-containment reserve, or safety valve denomination. Since quantity or price instruments realize endogenously and as special cases, the hybrid scheme then performs at least as well as both taken alone (Hepburn, 2009), and limits uncertainty about both emissions and abatement costs outcomes. From a policy perspective, Pizer, 2002 also highlights that hybrid schemes offer the flexibility and political appeal of an emissions trading scheme, with the credibility and transparency of a carbon tax.

The MSR experience. The short history of the MSR makes it difficult to thoroughly assess the performance of its support and stability functions. Yet, a preliminary feedback by analysts showed that it successfully resulted in reducing auction volumes by almost 397 million allowances in 2019, corresponding to 24% of the surplus (Marcu et al., 2020). This supply cutback could have enabled prices to recover quickly after the Covid-19 lock-down in March 2020. However, the 2018 price surge, which preceded action by the MSR, suggests a limited price-quantity correlation in the EU-ETS. Recent empirical studies emphasize that other factors such as speculation (Friedrich et al., 2019) and hedging (Tietjen, Lessmann, and Pahle, 2020) could have played an even more important part than the supply tightening in the recent price rise, and questions the long-term ability of the MSR to uphold prices. Moreover, the literature has expressed serious doubts about its stability function, all the more in the presence of a cancellation mechanism. Although it reinforces the support function on paper, by endogenizing the emissions ceiling, the cancellation mechanism has been accused of creating more price volatility for the additional uncertainty it creates (Kollenberg and Taschini, 2019; Osorio et al., 2020; Richstein, Chappin, and Vries, 2015). Besides, Gerlagh, Heijmans, and Rosendahl, 2019 and Hintermayer, 2020 pointed out that it put the EU-ETS at risk of a green paradox if the market anticipates the future cancellation of allowances.

Towards a hybrid EU-ETS ? In face of these weaknesses, a carbon price floor has been presented as a simple and transparent remedy to support and stabilize carbon prices. Perino, 2018 recognizes indeed that *« the complexity [of a cap-adjusting supply management mechanism] keeps scholars busy, but does not seem to serve any other meaningful purpose»*. By enabling market actors to anchor expectations about future prices, earlier works by Grüll and Taschini, 2011 and Fell et al., 2012 highlight that a price floor could help stabilize prices in the emissions trading schemes. However, Hintermayer, 2020 raise that the design of a price floor should be carefully chosen as it can greatly impact the number of allowances cancelled, and emissions *in fine*. Design options considered usually draw on international experience, as price floors are present in the RGGI, California and Quebec emission trading schemes (Flachsland et al., 2018). For instance, Brink, Vollebergh, and Werf, 2016; Boehringer and Fischer, 2018 focused on an auction reserve price and a fixed or variable carbon tax (i.e. a carbon price support). They find the reserve price to be interesting in practice in that it preserves a market wide carbon price and improve the trading scheme's cost effectiveness (Fischer et al., 2019). On the contrary, a tax policy could amplify the waterbed effect without a European coalition, and lead to welfare losses in countries that are net permit sellers. However, (Fell and Morgenstern, 2010) emphasized the trade-off between certainty over abatement costs and the range of emissions. In case of a price collar, Murray, Newell, and Pizer, 2009 suggests to limit the amount of allowances that can be added in the market to preserve the environmental integrity of the system. In the EU-ETS, this could be done by turning the quantity bounds of the MSR into price bounds (Flachsland et al., 2018), i.e. a Price Stability Reserve (Osorio et al., 2020).

Investment decisions. *Ex-ante* simulations of the EU-ETS have emphasized the benefits of hybrid schemes over pure quantity control. Yet, studies rarely consider investment choices in productive capital, although the long-term development of clean production capacity is key to reach carbon neutrality (Falbo, Pelizzari, and Taschini, 2019). For example, a nuclear power plant construction project typically lasts 8 years, with a life expectancy of 20-50 years (Moreira, Gallinaro, and Carajilescov, 2013). Once investments have been initiated, the production technology becomes *locked-in* for a long time with important consequences on environmental delivery and the choice of an pollution control instrument in turn. When accounting for capacity development, Mauer, Okullo, and Pahle, 2019 find that the MSR does not need a cancellation mechanism by contrast to other studies, as it succeeds in triggering early investment in renewable capacity and permanent fossil decommissioning. Besides, theoretical analyses by Baldursson and Fehr, 2004 and Pommeret and Schubert, 2018 showed that investment decisions in cleaner capital can depend on the permit endowment of manufacturers. For instance, when the future cap is uncertain and investment is irreversible, banking and investment in clean capital are substitutes. In the context of the EU-ETS where the current surplus of permits is high, these interactions can have important implications on the performance of a price floor relative to the MSR.

4.3 Quantitative model

Set-up. Based on the model developed by Mauer, Okullo, and Pahle, 2019, we develop a Hotelling model of the EU-ETS power sector, conforming to current design. The electricity producer maximizes the discounted revenues from electricity sales with $P_t E_t$ over $t \in (0, T)$ periods. We assume a competitive electricity market. Electricity is produced thanks to fossil-based or renewable generation capacity $K_{F,t}$ and $K_{R,t}$, respectively, in which the producer decides to invest at a quadratic investment cost $H(I_{F,t})$ and $X(I_{R,t})$.[2] Productive capital deteriorates at a fixed rate δ_F and δ_R indeed. The production volume E_t then amounts to the sum of fossil and renewable-based production (equation 4.3.5), and is driven by a linear electricity demand growing at a rate of 1% annually.[3] Specifically, we assume a choke price for electricity of 50€/MWh and a price elasticity of -0.5 (Reiss and White, 2005).

By contrast to renewable generation, fuel F_t has to be purchased at a price $P_{F,t}$ as an input for fossil-based production. We pick coal as the carbon input, and assign it a unit price of 13€/MWh based on historical data. Coal use can then be converted to tonnes of CO_2 using an emissions intensity factor. Finally, to meet compliance on the carbon market, the power supplier can purchase pollution rights Z_t at price τ_t. The remaining allowances, if any, can be stored in a permit bank B_t. The set of equations describing the power producer's decisions reads[4]

$$\{\mathcal{P}\}: \max_{I_{F,t}, I_{R,t}, F_t, Z_t} \quad \sum_{t=0}^{T} \beta^t \left[P_t E_t - P_{F,t} F_t - H(I_{F,t}) - X(I_{R,t}) - \tau_t Z_t \right] \tag{4.3.1}$$

under the constraints

$$B_{t+1} = B_t + Z_t - F_t, \tag{4.3.2}$$
$$K_{F,t+1} = I_{F,t} + (1 - \delta_F) K_{F,t} \tag{4.3.3}$$
$$K_{R,t+1} = I_{R,t} + (1 - \delta_R) K_{R,t} \tag{4.3.4}$$
$$E_t = E_{F,t} + E_{R,t} \tag{4.3.5}$$
$$E_{F,t} \leq \min(K_{F,t}, F_t), \; E_{R,t} = K_{R,t} \tag{4.3.6}$$
$$E_{F,t}, E_{R,t}, F_t, Z_t, K_{F,t}, K_{R,t}, B_t \geq 0 \tag{4.3.7}$$

where t is the time index, and F and R indices for fossil and renewable energy, respectively. β stands for the discount rate set at 10% (Oxera, 2011).

On the emissions trading scheme, allowances are supplied by an auctioneer who maximizes revenue from sales

$$\{\mathcal{A}\}: \quad \max_{Q_t} \sum_{t=0}^{T} \beta^t \tau_t Q_t \tag{4.3.8}$$

[2]The intercept and slope of investment cost functions are calibrated to reproduce observed investment levels in renewable and fossil capacity in 2018.

[3]This amounts approximately to a 20% increase in fuel consumption by 2050, consistent with PRIMES simulations

[4]The model was implemented using GAMS Knitro solver.

under the constraint

$$Q_t \leq C_t,\ Q_t \geq 0 \tag{4.3.9}$$

where C_t and Q_t are the periodical emissions ceiling and realized auction, respectively. Conforming to the design of the EU-ETS, the ceiling C_t is governed by a linear reduction factor LRF_t that sets the rate of decline of the emissions target, and the absorption rate of the MSR. The MSR can indeed intake (release) a volume $A_{in,t}$ ($A_{out,t}$) of allowances from auctions depending on the realized surplus of allowances. The dynamics of the auction ceiling then read

$$\begin{aligned} C_t &= \bar{C}_t - A_{in,t} + A_{out,t} \\ \bar{C}_{t+1} &= C_t(1 - LRF_t) \end{aligned} \tag{4.3.10}$$

In its current design, a cancellation mechanism (CM) has been appended to the MSR, making it cap-adjusting (i.e. auctions are not only shifted in time but allowances can permanently be cancelled). Starting in 2023, the CM intervenes when the volume of allowances in circulation or aggregate permit bank exceeds the previous year's auction volume. If applicable, the difference will be cancelled, implying an irreversible strengthening of the emission target. In turn, the MSR read

$$MSR_{t+1} = \begin{cases} MSR_t - A_{out,t} + A_{in,t} & \text{if} \quad t \leq 2023 \\ \min\{MSR_t - A_{out,t} + A_{in,t},\ C_t\} & \text{if} \quad t > 2023 \end{cases} \tag{4.3.11}$$

We admit that actual MSR rules are more intricate (specific rules apply to backloading and unallocated allowances)[5], but our model captures the main dynamics.

Calibration. Parameters for our emissions trading system follow closely the EU-ETS Directive. First, the linear reduction factor is set to 1.74% but increases to 2.2% after 2021, conforming to Phase IV revision.

$$LRF_t = \begin{cases} 0.0174 & \text{if} \quad t \leq 2021 \\ 0.022 & \text{if} \quad t > 2021 \end{cases} \tag{4.3.12}$$

Second, trigger quantity upper and lower thresholds for intervention of the MSR amount to 833 million and 400 million, respectively. The rate of intake of the MSR is initially set at 24% of the following year's auction volume and 12% after 2021. Besides, the outtake rate corresponds to a maximum of 100 million EUA yearly. In summary, the MSR grows as follows

[5]See European Commission for details

$$A_{in,t+1} = \begin{cases} 0.24 \times B_t & \text{if} \quad B_t \geq 833 \quad \text{and} \quad t \leq 2021 \\ 0.12 \times B_t & \text{if} \quad B_t \geq 833 \quad \text{and} \quad t \geq 2021 \\ 0 & \text{if} \quad B_t < 833 \end{cases} \tag{4.3.13}$$

$$A_{out,t+1} = \begin{cases} 100 & \text{if} \quad B_t \leq 400 \\ 0 & \text{if} \quad B_t > 400 \end{cases} \tag{4.3.14}$$

Importantly, and since we focus on the power sector only, we apply a correction factor to initial quantities relating to banked allowances, allowances seeded to the MSR in 2019, the MSR trigger thresholds, and the the auction ceiling. As such, we analyze the power sector holding the rest of industries covered under the EU-ETS fixed. The correction factor is defined based on the percentage share of allowances allocated to the power sector, that is approximately 73% according to 2017 emissions data. The initial (2018) bank size then amounts to 1.32 billion allowances, namely about a year worth of allowances. Second, the MSR is seeded with 1.48 billion allowances in 2019, corresponding approximately to 900 million back-loaded and 550-700 million unallocated allowances[6]. Its trigger thresholds are adjusted to the power sector's percentage share, boiling down to intake and outtake thresholds of 0.599 and 0.288 billion EUAs, respectively. The outtake rate is also scaled down to 72 million allowances. Finally, Phase III's initial gross auction ceiling is computed as the average of 2008-12 emissions in EU-ETS rules, and declines according to the LRF. Taking 73% of this quantity results in a ceiling of 1.27 billion tCO_2 for the power sector in 2018. A detailed discussion of parameter choices can be found in Mauer, Okullo, and Pahle, 2019, and a summary of parameters and initial values in the Appendix.

Model dynamics. Firstly, the current-value Lagrangian of the power supplier's problem $\mathcal{P}$ reads

$$\begin{aligned} \mathcal{L}^f = \sum_{t=0}^{T} \beta^t \Big\{ & P_t E_t(K_{F,t}, F_t, K_{R,t}) - P_{F,t} F_t - H(I_{F,t}) - X(I_{R,t}) - \tau_t Z_t \\ & + \lambda_t \big(B_t + Z_t - F_t - B_{t+1}\big) + \mu_t \big((1-\delta_f) K_{F,t} + I_{F,t} - K_{F,t+1}\big) \\ & + \eta_t \big((1-\delta_R) K_{R,t} + I_{R,t} - K_{R,t+1}\big) + \phi_T B_{T+1} \Big\} \end{aligned}$$

Where λ_t, μ_t and η_t are the non-negative shadow values of the bank, investment in fossil and renewable capacity, respectively. ϕ_{T+1} is the shadow value associated to the non-negativity constraint on B_{T+1}. Deriving the Lagrangian with respect to choice variables F_t, $I_{F,t}$, $I_{R,t}$ and Z_t (namely carbon input use, investment in fossil and renewable capacity

[6] https://ec.europa.eu/clima/policies/ets/reform

and allowance purchase) and setting them to zero results in the following first order conditions[7]

$$(F_t) : P_t E^F_t(K_{F,t}, F_t, K_{R,t}) - P_{F,t} - \lambda_t = 0 \tag{4.3.15}$$

$$(I_{F,t}) : H^{I_F}(I_{F,t}) - \mu_t = 0 \tag{4.3.16}$$

$$(I_{R,t}) : X^{I_R}(I_{R,t}) - \eta_t = 0 \tag{4.3.17}$$

$$(Z_t) : \tau_t - \lambda_t = 0 \tag{4.3.18}$$

Condition 4.3.15 first says that the marginal revenue product of energy sales must be equal to the total marginal cost of the carbon input, namely P_F plus the shadow cost of using an emission allowance λ_t. In equilibrium, the latter is equal to the permit price in each period (condition 4.3.18). Moreover, equations 4.3.16 and 4.3.17 imply that fossil and renewable capacity develops until the respective marginal cost of investment equals revenue generated from the additional capital.

To grasp the evolution of state variables over time, we further take derivatives of $\mathcal{L}^f$ with respect to $K_{F,t+1}$, $K_{R,t+1}$, B_{t+1}, B_{T+1}:

$$(K_{F,t+1}) : -\mu_t + \beta P_{t+1} E^{K_F}_{t+1}(K_{F,t+1}, F_{t+1}, K_{R,t+1}) + \beta(1-\delta_F)\mu_{t+1} = 0 \tag{4.3.19}$$

$$(K_{R,t+1}) : -\eta_t + \beta P_{t+1} E^{K_R}_{t+1}(K_{F,t+1}, F_{t+1}, K_{R,t+1}) + \beta(1-\delta_R)\eta_{t+1} = 0 \tag{4.3.20}$$

$$(B_{t+1}) : -\lambda_t + \beta\lambda_{t+1} = 0 \tag{4.3.21}$$

$$(B_{T+1}) : -\lambda_T + \phi_T = 0 \tag{4.3.22}$$

First note that 4.3.21 combined with 4.3.18 gives the Hotelling rule $\tau_t = \beta\tau_{t+1}$. Second, conditions 4.3.19 and 4.3.20 describe the dynamics of μ_t and η_t, which drive the development of fossil and renewable-based generation capacity, respectively. It appears that it differs from the depreciation-adjusted Hotelling growth in that it also depends on potential earnings generated by a marginal increase in capital size, $E^{K_F}_{t+1}$ and $E^{K_R}_{t+1}$. For instance, whenever $E^{K_R}_{t+1}$ is positive, $\eta_t > \beta(1-\delta_R)\eta_{t+1}$ so the firm has an incentive to grow renewable capacity immediately (the same reasoning applies for fossil). Alternatively, if $E^{K_R}_{t+1} = 0$ (the new capacity does not generate any earnings), $\eta_t = \beta(1-\delta_R)\eta_{t+1}$, meaning that capacity investment at time t will only correspond to the replacement worn out capital. Additionally, the non-negativity condition on the terminal permit bank has that $\phi_T B_{T+1} = 0$, since the constraint is binding ($\phi_T > 0$) whenever $B_{T+1} = 0$. Since the shadow value of an allowance λ_t must be positive anytime, equation 4.3.22 implies that $\phi_T > 0$ and $B_{T+1} = 0$ in turn. Classically, this implies that no allowance must be left in

[7] Only the conditions that are relevant to our discussion are reported for concision.

the bank after the end of the emissions trading program.

Let us now turn to the auctioneer's problem $\mathcal{A}$. Its current-value Lagrangian reads

$$\mathcal{L}^a = \sum_{t=0}^{T} \beta^t \{ \tau_t Q_t - \lambda_t (C_t - Q_t) \} \tag{4.3.23}$$

which has two the first order conditions

$$(Q_t) : \tau_t - \lambda_t = 0 \tag{4.3.24}$$

$$(\lambda_t) : C_t - Q_t = 0 \tag{4.3.25}$$

In equilibrium, the auctioneer sells all allowances made available by the legal emissions ceiling to the power supplier at a positive market clearing price τ_t. Combining first order conditions of the power supplier and the auctioneer leads to the market clearing condition

$$Q_t = Z_t \tag{4.3.26}$$

Note that the magnitude of allowance price thus increases with the regulatory constraint, namely the volume of allowances sold in auction.

Then, how does the stringency of the emissions cap interact with investments in low-carbon power generation? The evolution of capital size can differ from the mere replacement of depreciated assets indeed, since potential revenues can arise from capacity development. The extent to which the power supplier chooses to invest in renewable or fossil based generation can be analyzed by combining the equations describing the capacity development dynamics (4.3.19 and 4.3.20):

$$\frac{\eta_t - \beta(1-\delta_R)\eta_{t+1}}{\mu_t - \beta(1-\delta_F)\mu_{t+1}} = E_{t+1}^{K_R} / E_{t+1}^{K_F} \tag{4.3.27}$$

The left, non-negative member of the above equation represents the ratio of investments in renewable capacity (beyond capital replacement) relative to fossil. Intuitively, it hinges on the relative marginal earnings generated by new capital, as described by the right member of the equation. Going back to the model description, recall that instantaneous electricity production amounts to the sum of fossil and renewable-generated power, namely $E_t = EF, t + E_{R,t}$. While renewable production only depends on the size of generation capacity, fossil-based production is bounded by the emissions ceiling which limits the use of hydrocarbon inputs. In turn, and drawing from the model description, we can re-write the energy supply equation $E_t = min(K_{F,t}, F_t) + K_{R,t}$. Equation

4.3.27 can then be re-written

$$\frac{\eta_t - \beta(1-\delta_R)\eta_{t+1}}{\mu_t - \beta(1-\delta_F)\mu_{t+1}} = \begin{cases} 1 & \text{if} \quad K_{F,t+1} < F_{t+1} \\ \geq 1 & \text{if} \quad K_{F,t+1} \geq F_{t+1} \end{cases} \tag{4.3.28}$$

As long as the producer does not anticipate fossil generation to be constrained by emissions but the size of capacity, there is not preference to develop one type of capital or the other. However, as soon as the emissions trading scheme bounds the use of carbon inputs, the incentive to invest in renewable generation becomes greater. With a credible environmental target, we should see investments shift from fossil to renewable generation, and clean capital gradually replace the brown one as fossil capacity wears out. However, any anticipation of an effective cap relaxation could revive the development of fossil capacity, as in a large permit bank or an injection of allowances in the market from the MSR.

Stochastic demand. In our simulations, we also want to compare the outcomes of the EU-ETS in presence of the MSR or price support policies in case unexpected economic shocks arise. To introduce uncertainty in the model, we assume that in each period from 2019 to 2030, energy demand either remains unchanged or grow at a linear 2% rate with equal chances. Equivalently, we assume that the power price fluctuates around its expected path. In turn, uncertainty grows with the time horizon. The model is solved using stochastic programming methods as in Albers, 2011. More precisely, the firm knows the probabilistic structure of the future but the realization of a particular shock is unknown until she observes it. Besides, her belief structure remains fixed through time but recourse actions compensating for past decisions are possible.

4.4 Policy scenarios

This Section presents three carbon price floor policies selected for our comparative analyses: (i) a tax on emissions, (ii) an auction reserve price (AR) and (iii) a carbon price support (CPS). These policies have either been discussed in the literature or put forward by policy makers in the past. They are comparable in that they secure the same minimum price of carbon on the EU-ETS power sector.

Auction reserve price. Set at the price floor, an auction reserve price ensures that allowances are at least as expensive when auctioned. In our setting, this is achieved by giving the auctioneer a possibility to remove y_t allowances from auctions for a reserve price $\underline{p}$. When given this option, the auctioneer would find it profitable to remove allowances from auctions whenever the market clearing price is lower than $\underline{p}$. In turn, this mechanism indirectly adjusts the auction volume to deliver a market clearing price higher than the price floor.[8] For the sake of comparison with the MSR, we assume that removed allowances in question are cancelled out, instead of put in the reserve. Besides, the quantity of allowances that can be removed from auction is only limited by the legal auction ceiling itself.[9]

In presence of an auction reserve price, the auctioneer's program becomes

$$\max_{Q_t, y_t} \sum_{t=0}^{T} \beta^t \left[\tau_t (Q_t - y_t) + \underline{p} y_t \right] \quad \text{such that} \quad Q_t \leq C_t,\ (Q_t - y_t) \geq 0,\ y_t \geq 0$$

The last, non-negativity constraint on the volume of allowances removed from auctions is important since it determines by how much the allowance price rises above the price floor $\underline{p}$. Intuitively, when the price floor is not binding, the auctioneer would find it profitable to buy allowances at a price $\underline{p}$ and sell them in auction. However, the non-negativity does not allow this behavior, preventing in turn that the price sticks at the floor. Denoting ψ_t the multiplier associated with the non-negativity constraint on y_t, and combining the first order condition of the above problem with respect to Q_t and y_t, it appears that[10]

$$\tau_t = \max\{\underline{p}\ ,\ \underline{p} + \psi_t\} \tag{4.4.1}$$

Namely, the allowance price is the maximum of the price floor and the auction market clearing price when above the floor. More precisely, the auctioneer starts removing allowances from auction ($y_t > 0$) whenever τ_t hits the price floor. Since the non-negativity does not bind, $\psi_t = 0$ and $\tau_t = \underline{p}$. By contrast, when $\tau_t > \underline{p}$, the non-negativity constraint on y_t binds and $\psi_t > 0$. The allowance price then grows at the usual rate of discount as long as their is a positive permit bank. When invoke, the auction reserve price will in turn cutback the auction volume and increase permit scarcity. We should therefore observe a thinner bank and a shorter banking period.

Tax on emissions. The application of a extra fee on acquittal of emissions permits has been put forward by Wood and Jotzo, 2011, Brink, Vollebergh, and Werf, 2016 and Boehringer and Fischer, 2018, mainly for its relatively simple implementation and budgetary advantages. Intuitively, it secures a minimum effective carbon price at the level of the price floor, regardless of outcomes on the permit market. In the extreme case where

[8]Our auction reserve price is implemented in a similar way than Fell et al., 2012 and Hintermayer, 2020's buyback program.

[9]This implies that the allowance price could drop below the floor in the extreme case where the economic activity completely stops and the whole auction volume has already been removed from the auctioneer.

[10]For simplicity, we realistically assume that the number of allowances removed from auction never approaches the total auction volume, i.e. $(Q_t - y_t) \geq 0$ never binds.

the allowance price sharply falls because of a major economic shock, like in Phase II of the EU-ETS, the price of carbon would still be maintained by the tax. In the power producer's objective, introducing a tax simply boils down to an additional cost term $T_t F_t$, with $T_t = \underline{p}$ the extra fee. The first order condition describing fossil-based electricity production decisions then turn into

$$\tau_t = (P_t E_t^F(K_{F,t}, F_t, K_{R,t}) - P_{F,t}) - \underline{p} \tag{4.4.2}$$

In words, the marginal revenue product from electricity sales has to sum up to the allowance price on the permit market and the extra fee, set at the price floor. As the tax exogenously scales up the marginal cost of fossil-based electricity regardless of the production volume, it scales down the allowance price on the emissions trading scheme by the same amount. More precisely, the tax frees up allowances on the permit market, relaxing future permit scarcity, hence lowering EUA prices. In the presence of a tax on emissions, we should therefore observe a larger bank and a longer banking period relative to the baseline case. We acknowledge that our single sector framework doesn't allow an assessment of the waterbed effect potentially generated by a tax in a partitioned environment. Boehringer and Fischer, 2018 showed that if implemented unilaterally, an tax on emissions can in fact reduce abatement demand domestically, which increases the supply of allowances elsewhere. However, Phase II trading data reveals that more than 65% of over-the-counter exchanges remains within the power sector. Although we cannot track the journey of allowances passing through the hands of financial intermediaries (this would require to earmark permits), this suggests that the waterbed effect would be small.

Carbon price support. First introduced in the UK power sector in 2013, a carbon price support (CPS) consists in a top-up levy (or variable fee) on allowance prices.[11] Unlike a fixed fee, the magnitude of a CPS is endogenously determined as the difference between the price floor and the realized market clearing price of allowances. Therefore, we can define it as

$$CPS_t = \max\{0\ ,\ \underline{p} - \tau_t\}$$

Note that the support only takes action when the market clearing price falls below the price floor. In our model, the CPS adjusts instantaneously to allowance price variations[12] by contrast to the UK experience, where it only changes every three years due to practical

[11] In the UK, it was supposed to increase from 5/tCO_2 to 30 in 2020, before being frozen at 18/tCO_2 for political reasons. Leroutier, 2019 attributes it a 104-150$MtCO_2$ emissions reduction.

[12] In GAMS, it is implemented as an iterative process. The model is first solved with $CPS_t = 0$, in a second iteration it adjusts to $CPS_t = \underline{p} - \tau_t$, and so on until it converges to a steady state.

constraints. In the power supplier's objective, the introduction of a CPS resembles that of a tax: an additional cost term $CPS_t F_t$ accounts for the variable fee on emissions. The first order condition describing fossil-based electricity production decisions then turn into

$$P_t E_t^F(K_{F,t}, F_t, K_{R,t}) - P_{F,t} = \max\{\tau_t \ , \ \underline{p}\} \tag{4.4.3}$$

Namely, the net marginal revenue product from selling fossil-generated power cannot fall below the price floor thanks to the carbon price support. Unlike the fixed fee however, the CPS only affects the effective carbon price below the price floor. Above it, the allowance price entirely embodies the marginal cost of pollution. In turn, we expect a smaller size of the permit bank than under a fixed tax since it is more flexible.

4.5 Results

This Section presents the market, investment and emissions outcomes of the EU-ETS power sector, in the presence of the current MSR or alternative price floor policies. The deterministic simulations first enable us to grasp how policies achieve a minimum CO_2 price, and second, stochastic simulations allow to test the support and stability functions of each policy by comparison to the MSR. In turn, a reference scenario denoted *status quo* corresponds to the MSR as described in Section 4.3. Next, three scenarios named after carbon price floor policies described in Section 4.4 are run, absent the MSR and keeping everything else unchanged. We choose a price floor of 30€/tCO_2, which has been put forward in recent policy discussions.[13]

4.5.1 Deterministic setting

Figure 4.5.1 presents simulated market outcomes from 2019 to 2027.[14] First, note that the tax and the carbon price support yield consistently different results than the auction reserve price. Recall indeed that these price support policies entail two different mechanisms. While the auction reserve price directly works on auction volumes, an extra (fixed or variable) fee scales up the effective price of emissions without recurring to the permit market.

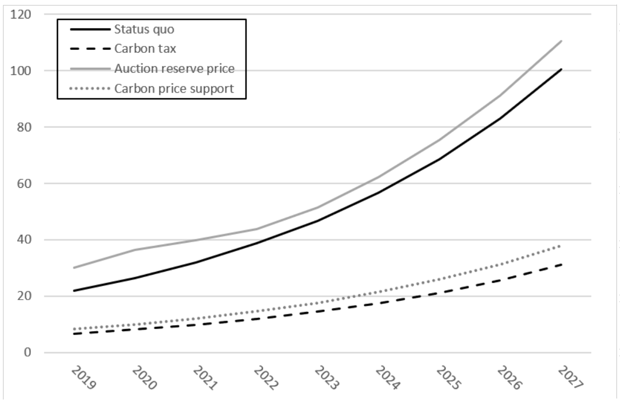
Therefore, the tax and the CPS lead to a strong decrease in emissions relative to the *status quo* in the short run, as the effective carbon price rises. This frees up a large quantity of

[13] We also ran simulations with a price floor of 25€/tCO_2 and 35€/tCO_2, but the policy ranking remained unchanged.

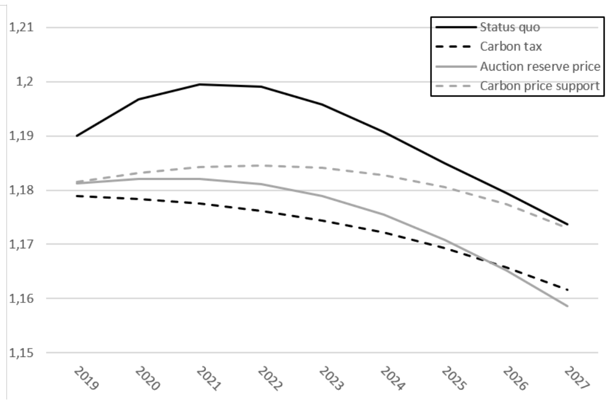
[14] To limit the computational time, simulations are ran on 10 periods.

FIGURE 4.5.1: Deterministic market outcomes

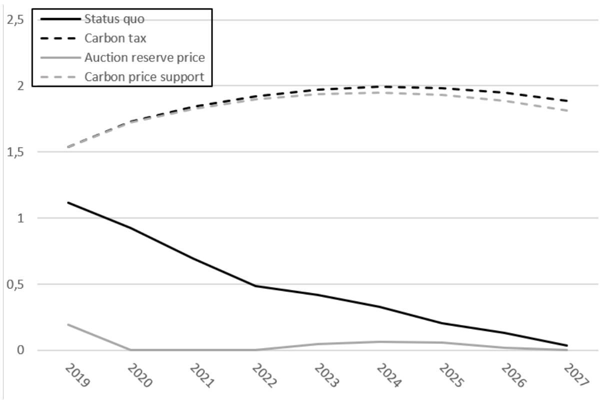
(A) Allowance prices (€/tCO_2)



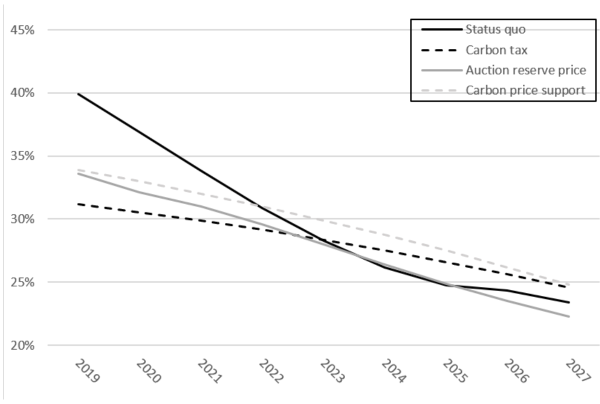
(B) Emissions (bn tCO_2)



(C) Permit bank (bn EUA)



(D) Share of investment in fossil capacity



allowances on the market, as panel (c) shows: the size of the permit bank remains at 1.5-2 billion EUA, which exceeds the periodical auction volume. Because of the low permit scarcity, allowance prices remain around 5-25€/tCO_2.[15] Moreover, the rate of emissions decrease slows down relative to *status quo*. Looking at panel (b), a CPS even lead to higher emissions than the baseline after 2027. This is due to the carbon price support only kicking in when the EUA price falls short of the price floor, whereas a fixed tax scales up the effective price of carbon at all times[16]

By contrast, the auction reserve price alters auction volumes to achieve the carbon price floor, hence an allowance price of 30€/tCO_2 minimum in the EU-ETS power sector (panel (a)). In turn, the reserve price results in cutting back the power producer's permit bank relative to the *status quo*. This is due to the auctioneer cancelling out excess

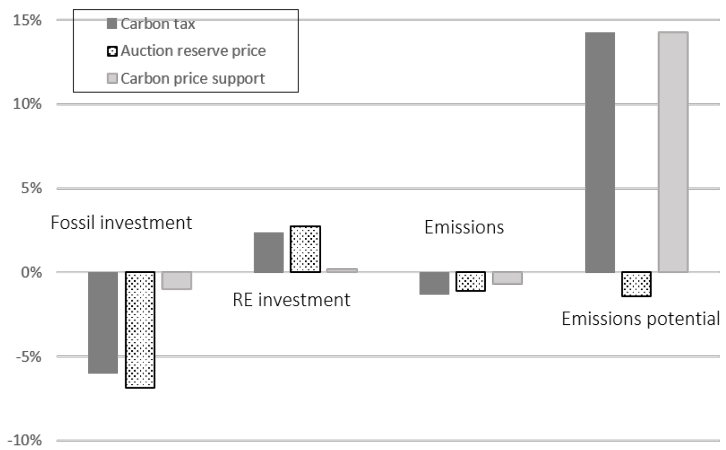
[15]Prices are reported in current value.

[16]In our simulations, the CPS kicks in over the entire period, since the present value of the allowance price is lower than that of the price floor.

allowances when the reserve price takes action, as opposed to the MSR withdrawing a limited volume of permits. More precisely, the auction reserve price led to 100% of the permit supply being cancelled in 2019, 28% in 2020, 8% in 2021 and 6% in 2022. Over the same period, the MSR intook 24% of the annual permit bank and cancelled 940 million allowances in 2023 due to the cancellation mechanism, yet its effect is more moderate. As a result, short-term emissions reductions are greater under an auction reserve price.

Moreover, panel (c) and (d) of Figure 4.5.1 suggest that the development of power generation capacity is linked to the permit bank, as put forward in Baldursson and Fehr, 2004 and Pommeret and Schubert, 2018. For instance, the auction reserve price and MSR induce the fastest disinvestment in fossil to the benefit of renewable capacity. This results from the cap-adjusting nature of these policies, due to allowance cancellations. The cancellation mechanism visibly accelerates disinvestment in fossil in 2023 indeed. Interestingly, tax and CPS increase the share of investment in renewable capacity at the outset, but yield a slower rate of disinvestment in fossil. The extra fee on emissions makes polluting electricity production more costly in the short-run indeed, yet the large bank provides an incentive to maintain fossil-based generation capacity.

FIGURE 4.5.2: Cumulative investment in capacity and emissions over 2019-27



Note: The y-axis represent cumulative outcomes over the period, as a percentage difference to the status quo. For instance, investment in fossil capacity is about 6% lower under an auction reserve policy than under the status quo. Emission potential is computed as the sum of observed emissions and the 2027 bank.

Finally, Figure 4.5.2 represents cumulative capacity investments and emissions relative to the *status quo* over 2019-27. Reaching carbon neutrality implies to durably curb the stock of pollutants in the atmosphere indeed. First, carbon tax and auction reserve price reduce cumulative investments in fossil capacity by 4-6% relative to the *status quo*, and perform better to steer investment in clean capital. Second, all three price floor policies manage to cutback cumulative emissions to a small extent (1-2% relative to the baseline). However, the ranking of policies reverses when accounting for the leftover bank at the end of the period, as in *emissions potential*. The carbon tax becomes clearly outperformed by the *status quo*, by more than 12%. Besides, a carbon price support seems counter-productive, since no improvement is made in terms of investment, although the emissions potential is large.

4.5.2 Stochastic results

Stochastic simulations put the support and stability functions of both MSR and price floor policies at test when future demand for energy is uncertain. Recall indeed that the MSR has been implemented to (i) control the permit surplus and (ii) to improves the system's resilience to major shocks. In what follows, the *high* and *low* labels refer to scenarios where demand successively grows at an unexpected 2% rate of remain unchanged.

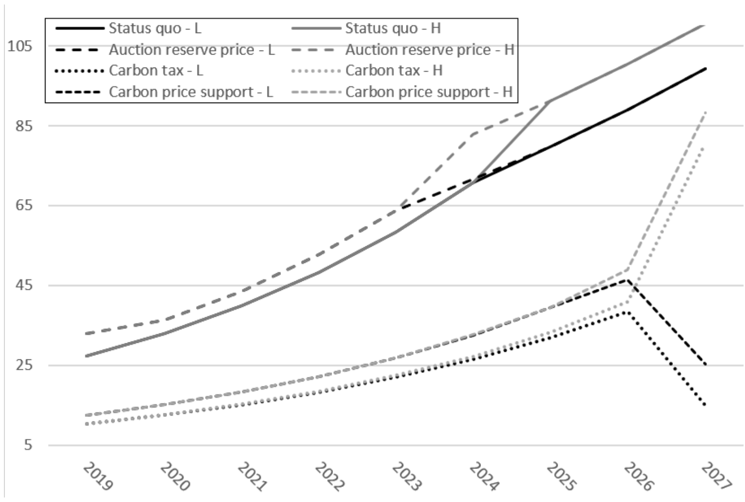
First, panel (a) of Figure 4.5.3 reveals that high (resp. low) demand shocks drive the allowance price up (resp. down) on the permit market regardless of the policy. Price dynamics are indeed driven by unexpected variations in the production activity, and the development of the permit bank in turn. For instance, panel (b) shows that positive demand shocks result in emptying the permit bank, which suggests a larger share of fossil-based electricity production. The production capacity being relatively locked in the short run because of investment costs in renewable capacity, the power producer has no choice but to use banked allowances to cover unplanned carbon emissions.

Second, permit price and bank fluctuations are less marked under the *status quo* or an auction reserve price, than under a fixed or variable carbon tax. This is due to the bank being almost depleted in early periods under supply-adjusting policies, leaving less room for inter-temporal arbitrages. With no allowances in reserve, prices reflect the realized level of energy demand indeed, and grow linearly according to our modeling assumptions.[17] By contrast, a larger bank is correlated with a higher price volatility in our simulations, due to the wider range of emission outcomes, like under a fixed and variable carbon tax. In particular, both instruments fail to maintain EUA prices when demand turns out to be lower than expected as a result of the accumulated bank. In the high demand scenario however, allowances prices suddenly increase up to 85€/tCO_2. This can be explained by the fast adjustment of coal usage to unexpected production needs.

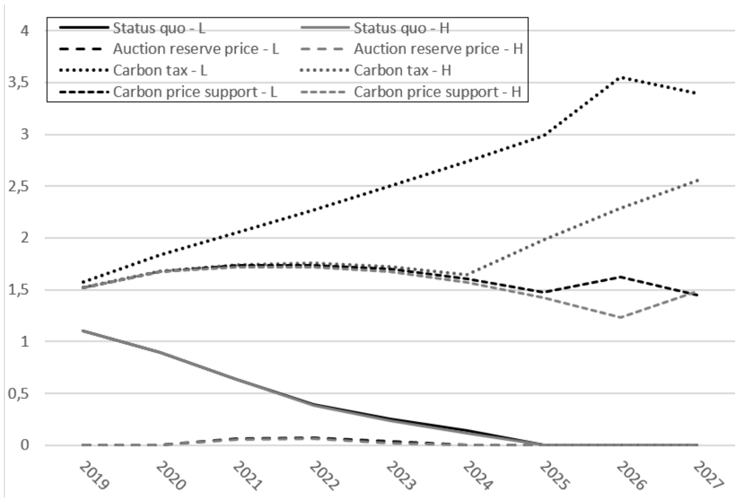
[17] Recall that energy demand grows linearly.

FIGURE 4.5.3: Stochastic market outcomes

(A) Allowance price



(B) Permit bank (bn EUA)

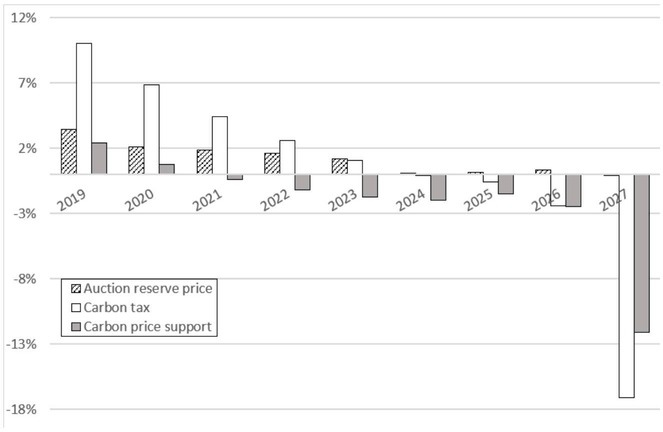


Therefore, Figure 4.5.3 reveals that supply-adjusting policies like the MSR and an auction reserve price lead to higher, less volatile allowance prices in case of an economic downturn. Moreover, we find that the EU-ETS power sector, in its current design, delivers allowance prices above the floor (30€/tCO_2) after 2021, hence complementary price floor policies are unnecessary. In particular, the MSR price support function is not outperformed by any of the price floor policies in presence of a negative demand shock.

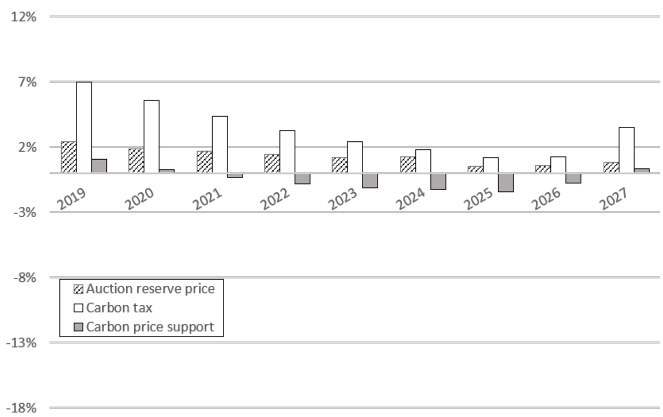
Taking stock of the above, we now analyze implications for the medium-run decarbonization of EU-ETS power sector. Figure 4.5.4 reports the share of investment flows in green capital in percentage change relative to *status quo*. First, we learn that when demand is unexpectedly high, the fixed carbon tax steers more investment in green capital than the MSR. However, both fixed and variable taxes do not manage to maintain

FIGURE 4.5.4: Investment in renewable production capacity

(A) Low demand



(B) High demand



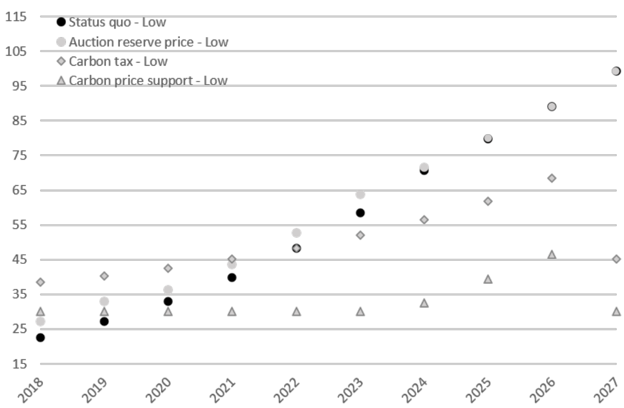
Note: Values are computed as the percentage difference to the *status quo*.

green investment when demand is unexpectedly low. Investment decisions are indeed strongly correlated with effective pollution prices pollution prices faced by the producer, Figure 4.5.5 shows. When demand is sluggish, permits are so abundant on the market that the additional fee does not compensate the low allowance price. Consequently, the effective pollution price drops to the floor in 2027 (panel (a)). By contrast, supply-adjusting policies shield (at least partly) the effective price of carbon from economic downturns, since most of the permit surplus is already absorbed or cancelled. Our results are thus in line with Pommeret and Schubert, 2018, namely banking and green investment are substitutes. Yet, 4.5.5 shows that carbon prices can quickly get out of control in case of a positive demand shock, as a result of permit cancellations. This is particularly salient under an auction reserve price, which does not have the ability to inject permits back in the market, i.e. a safety valve.

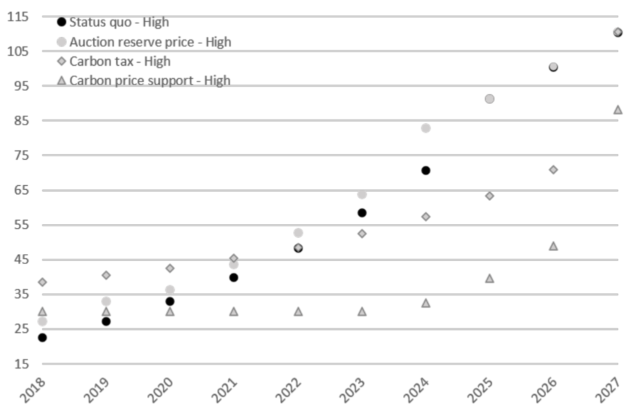
Besides spurring investment in clean capital, dismantling fossil-fired capacity is crucial to achieve carbon neutrality in the long run. Accordingly, Figure 4.5.6 shows the rate of fossil decommissioning in the low and high demand scenarios. First, simulations reveal that until 2025 (2026 in the high demand scenario), production capacity grows at a decreasing rate, except in the first years under a fixed carbon tax. Second, the MSR and the auction reserve price are superior to carbon taxes when demand is low, and lead to the decommissioning of approximately 2.5% of the 2026 capacity. In the high demand scenario however, the ranking of policies is unclear. Surprisingly, fossil decommissioning starts later and to a smaller extent, suggesting that favorable economic conditions may not be synonym of faster energy transition. Therefore, our results suggest that, once again, supply-adjusting policies are superior to additional fees on the permit price. Carrying a permit bank may indeed incentivize firms to maintain their fossil generation capacity.

FIGURE 4.5.5: Effective pollution price

(A) Low demand



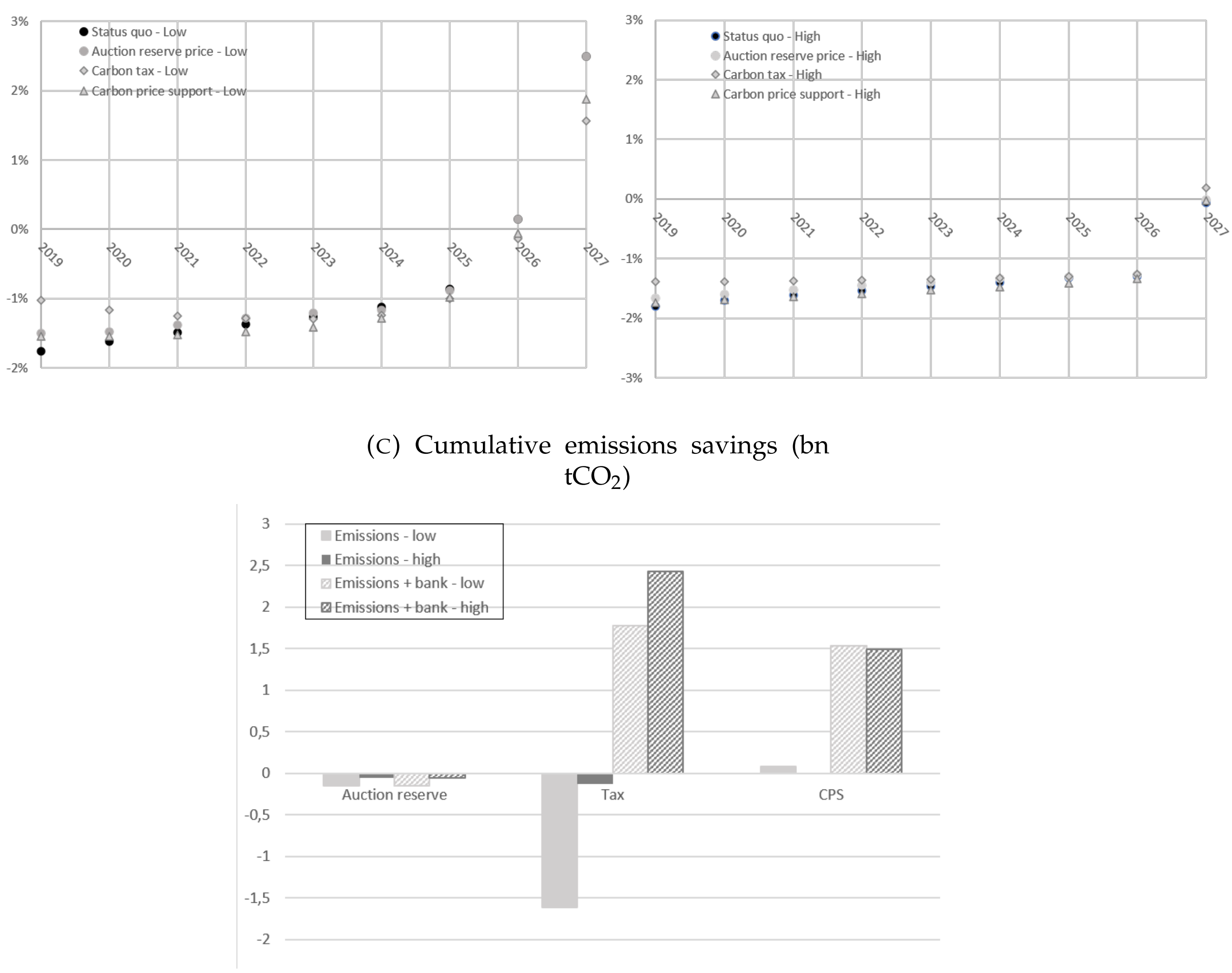
(B) High demand



Note: The effective pollution price reports the actual price of carbon faced by the producer, taking into account the allowances price support.

Finally, we evaluate the ability of price floor policies to cutback emissions. Panel (c) of Figure 4.5.6 represents cumulative emissions savings by comparison to the *status quo* under three price floor policies. Looking at the plain bars, it appears that when energy demand is low, a fixed carbon tax leads to cut back 1.6 bn tonnes of CO_2 (out of 10-12bn CO_2 in total) relative to the MSR the over the 2018-27 period. This is due to the effective price of pollution being higher from 2019 to 2022 (Figure 4.5.5), which deters pollution although permits are abundant. A variable tax results in increasing emissions though, as a result of the effective price of carbon being lower than the tax (it remains at 30€/tCO_2 until 2024) while freeing up allowances. When demand is high however, policies perform equally well, confirming that the choice of an instrument mainly depends on its performance in unfavorable economic conditions. Yet, and similarly to the deterministic case, fixed and variable taxes perform poorly when accounting for the leftover bank, because they shift emissions in time instead of adjusting supply.

FIGURE 4.5.6: Fossil decommissioning and emissions savings



(A) Low demand

(B) High demand

(C) Cumulative emissions savings (bn tCO_2)

Note: Panel (a) and (b): the y-axis indicates the percentage of fossil-generation capacity decommissioned every year, accounting for investment flows and capital depreciation. Negative values indicate an increase in fossil capacity, and positive value the decommissioning of capacity. Panel (c): negative values indicate emissions savings, positive values emission increases.

4.6 Discussion

This study addresses the support and stability functions of the MSR, in its current design, by comparison of carbon price floor policies in the EU-ETS power sector. We focus on three plausible policies that secure the same minimum effective price of carbon: (i) an auction reserve price, (ii) a UK-style carbon price support and (iii) a flat tax on emissions. By contrast to previous *ex-ante* evaluations of the MSR and price floor policies, we take into account the development of power generation capacity, which can be fossil or renewable-based. We use a numerical model of the EU-ETS carefully calibrated to the power sector, and amended with current MSR rules and the cancellation mechanism.

In a first set of deterministic simulations, we learn that the design of a carbon price floor policy matters for market outcomes. For instance, an auction reserve price cuts back the permit bank to achieve a minimum price of CO_2, although a variable and fixed tax result in freeing up a large amount of permits on the carbon market. Therefore, we find that the size of the current permit surplus is decisive to choose an instrument. For instance, supply-adjusting policies like the current MSR and an auction reserve price yield greater emissions reductions in total as a result of permit removals from auctions. By contrast, implementing an extra fee on emissions may be counterproductive, and put the long-term environmental integrity of the EU-ETS power sector in jeopardy.

Second, running policy simulations when future energy demand is uncertain allows us to test the support and stability functions of the current EU-ETS equipped with the MSR, or three price floor designs. To do so, we assume that energy demand can either remain constant or grow unexpectedly high. First, we learn that at a target price floor of 30€/tCO_2, the support function of the MSR is not outperformed by any of the price floor policies. In our simulations, the EU-ETS power sector with the current MSR delivers effective pollution prices above the floor in 2020 and after indeed. Moreover, the support function of the MSR is robust to economic downturns as a result of permit cancellations. By contrast, an extra variable of fixed fee on emission does not manage to maintain the pollution price above the floor in case of a low demand shock, with consequences on green investment. These results suggest that support function of supply-adjusting policies like the MSR or an auction reserve price is superior to that of extra fees on emissions. Besides, permit cancellations trigger faster and durable decommissioning of fossil-based generation capacity, with long-term environmental benefits.

Furthermore, we find that the current MSR performs better than extra pollution taxes, and at least as well as an auction reserve price, to stabilize prices. By depleting the permit bank, supply-adjusting policies remove the possibility to make inter-temporal arbitrages indeed. In turn, the price trajectory is entirely driven by the realized growth of electricity demand, which is linear or constant in our case. By contrast, a high bank gives room for greater price swings under a fixed and variable carbon tax, especially when demand is unexpectedly low. However, if supply-adjusting policies perform well in presence of a negative shock, they may lead to uncontrollably high carbon prices in case of a positive shock. Our simulations report prices above 110€/tCO_2 in 2027 indeed. The possibility to inject permits back in the market, as in the MSR (a so-called *cost containment reserve* appears in the directive[18]), may therefore by important as it provides a safety valve if costs become too high. We acknowledge that our time horizon is too short to settle the question yet.

Therefore, we raise that a combination of the MSR and an auction reserve price, in the form of a *Price Stability Reserve*, as named by Osorio et al., 2020, can be an interesting alley for future research. Such a policy would indeed preserve the *safety valve* characteristic of the allowance reserve, while providing more certainty to market actors thanks to the price bounds. Furthermore, it would be advantageous from a budgetary perspective, since it would allow member states to lock minimum revenues from auctions.

[18]Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community, 2003 O.J. (L 140) 63, Art. 29a (1): "If, for more than six consecutive months, the allowance price is more than three times the average price of allowances during the two preceding years on the European carbon market, the Commission shall immediately convene a meeting of the Committee established by Article 9 of Decision No 280/2004/EC."

Appendix of Chapter 4

TABLE 4.6.1: Parameters and initial values

Variable	Description	Value
β	Annual discount rate	0.1
δ_F	Depreciation rate for fossil capacity	0.025
δ_R	Depreciation rate for fossil-free energy capacity	0.025
$P_{F,t}$	Unit price for coal (€/MWh)	13
	Emissions intensity factor for coal (tCO_2/MWh)	0.956
	Lower bound of unit costs of investment in fossil energy capacity (€/MWh)	800
	Upper bound of unit costs of investment in fossil energy capacity (€/MWh)	2200
	Lower bound of unit costs of investment in fossil-free energy capacity (€/MWh)	800
	Upper bound of unit costs of investment in fossil-free energy capacity (€/MWh)	6000
	Elasticity of energy demand	-0.5
	Growth rate of energy demand (Mean)	0.01
	Growth rate of energy demand (High)	0.02
	Growth rate of energy demand (Low)	0
	Choke price in 2018 (€/MWh)	50
	Adjustment factor: share of allowances banked by the power sector	0.73
	MSR in 2019 adjusted by the share of power sector (bn EUA)	1.48
	Upper threshold of bank adjusted by share of power sector (bn EUA)	0.599
	Lower threshold of bank adjusted by share of power sector (bn EUA)	0.289
LRF_t	Linear reduction Factor ($t \leq 2020/t \geq 2021$)	0.0174/0.022
$A_{in,t}$	Intake rate of the MSR ($t \leq 2023/t \geq 2024$)	0.24/0.12
$A_{out,t}$	Allowances withdrawn from the MSR adjusted by share of power sector (bn EUA)	0.073
$K_{F,2018}$	Generation capacity in base year for fossil energy (kilo TWh)	1.179
$K_{R,2018}$	Generation capacity in base year for fossil energy (kilo TWh)	1.497
E_{2018}	Total energy supply in first year (kilo TWh)	2.676
B_{2018}	Initial stock of banked allowances adjusted by the share of power sector (bn EUA)	1.32
C_{2018}	Initial auction volume adjusted by the share of power sector (bn EUA)	1.27

Note: Depreciation rate corresponds to the inverse of the average lifetime of a power plant, namely 40 years. Initial values for generation capacity are based on a report (https://ember-climate.org/wp-content/uploads/2018/01/EU-power-sector-report-2017.pdf) by Sandbag and Agora.

General Conclusion

This dissertation has investigated determinants of carbon price formation in the EU-ETS which emanate from the internal market structure. By providing a critical overview of past crises and reforms experienced by the EU-ETS, the first chapter shows that supply-side measures were mostly designed to shield the mechanism from external shocks to the market. The 2009 price drop was exclusively attributed to the financial crisis, overlapping policies and the massive use of international credits indeed. In turn, the design of the market stability reserve (MSR), which aims at supporting and stabilizing EUA prices since 2019, was based on the assumption of constant market fundamentals, i.e. marginal abatement costs and emission baselines. Thus, the internal market structure has been disregarded in models of the EU-ETS and policy design, just like in the two - static and dynamic - founding models of emissions trading: Montgomery, 1972 and Rubin, 1996. Therefore, this dissertation relies on empirical material, namely the transaction and compliance registry of the EU-ETS (the EUTL), to examine the validity of some key assumptions of the above models.

In the next two chapters, we find in *ex-post* analyses of the second (2008-2012) and third (2013-2020) trading periods that the market structure is unstable, both in its static and dynamic dimensions. Specifically, a second chapter provides empirical signs of trading costs, which affects market participation at the extensive (firms prefer not to trade at all) and intensive (trading decisions are sub-optimal) margin. According to the Coase theorem, the presence of transaction costs invalidates the static equi-marginal principle, hence weakening two fundamental advantages of emissions trading schemes: (i) the market allocates abatement efforts to the cheapest sources and (ii) compliance costs are minimized regardless of the initial allocation of permits. This result does not only affect compliance costs, but also the reaction of the market price as a result of a supply-side policies, and the choice of allocation method by the regulator. Besides, a third chapter shows that technological progress, by altering the level of counterfactual emissions, also affects the dynamic structure of the market. Specifically, and everything else equal, non-directed and directed technological progress tends to increase and decrease permit demand, respectively. This result implies that assumptions of (i) constant marginal abatement costs and (ii) constant emission baselines, as posed by Rubin, 1996, do not apply in practice.

Therefore, we emphasize that static and dynamic instabilities of the market structure may explain deviations of the price path from the Hotelling rule. Our results question the adequacy of the MSR to correct these instabilities, and the potential benefit of implementing a price floor to remedy these instabilities, by helping market actors anchor expectations about future EUA prices. The MSR has indeed been criticized by economists in that (i) its action is unpredictable, especially the number of allowances it will cancel, and (ii) it may create another layer of uncertainty in an already complex regulatory environment. We address this argument in a fourth chapter, in an *ex-ante* analysis of the EU-ETS power sector in the presence of either the MSR or three alternative price floor policies: an auction reserve price, a carbon tax or a UK-style carbon price support. Our results suggest that the key element to support and stabilize prices is to restore the short-term scarcity of permits, especially in the EU-ETS where the initial of surplus is high. Both instruments manage to do so: the MSR equipped with the cancellation mechanism and an auction reserve price. Our results thus suggest that the EU-ETS does not need to be turned into a «hybrid scheme», as long as the MSR removes - and cancels - enough permits in the first years.

More generally, this dissertation provides three main takeway to policymakers. First, firms make little benefit out of the flexibilities offered by the EU-ETS, both in terms of spatial and inter-temporal permit trading. More precisely, many gains from trade go unrealized due to transaction costs, and firms' inter-temporal permit management strategy rarely matches that dictated by theory. For instance, the data shows that over-allocated firms usually bank their permit surplus passively, and under-allocated ones can engage in passive forward borrowing. Most permit transaction (including derivative products allowing greater flexibility like futures) are held by financial actors indeed, who are responsible for about 80% of the total traded volume. These observations imply that for most regulated plants, the EU-ETS resembles a system of non-tradable pollution licenses, hence abatement efforts greatly depend on the allocation method and size. As an illustration, the power sector, which gets its permit through auctions, has been responsible for more than a quarter of the aggregate abatement efforts, although sectors that received permits for free (and rather generously) showed little improvements in their carbon-intensity ratio. Therefore, we argue that harmonizing the allocation method, by relying on full allowance auctioning, would be beneficial both in terms of effort sharing and economic efficiency.

Moreover, we saw that technological progress, among others, make permit demand unstable over-time, which can be a source of price volatility and further uncertainty for market actors. Knowing that uncertainty about future outcomes in the EU-ETS undermines investment in low carbon technologies by firms and private investors, it appears necessary to design policies that support and stabilize prices. The fourth chapter showed that the MSR could fulfill these objectives, conditional on removing enough allowances from the market. Indeed, restoring the short term scarcity of permits, hence limiting the range of emission outcomes, is critical, especially when firms' decisions depart from theoretical predictions. We argue in turn that full auctioning combined with a stringent MSR could lead to similar results as an auction reserve price, with the advantage of consistency and feasibility from a political point of view.

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Abstract

The European Union Emissions Trading Scheme (EU-ETS) is referred to as the cornerstone of the EU's fight against climate change. However, its ability to durably put the economy on a low-carbon path and eventually reach long-term climate targets has been questioned. Carbon prices delivered have been judged too low and volatile to trigger the necessary investments in a cleaner production, and permanently phase out fossil fuels indeed. Price outcomes were largely attributed to a supply imbalance of permits due to external shocks: supply-side reforms, critically reviewed in a first chapter, were in turn conducted to shield the EU-ETS from them, with limited success.

Yet, most prospective analyses of the EU-ETS rest on archetypal models of emission trading, which disregard its market structure. Therefore, this dissertation contributes to better understand price formation in the European carbon market by investigating structural drivers of permit prices, appraising their impact on market outcomes and policy design. Motivated by transaction and compliance data, the second and third chapters provide *ex-post* analyses of the second (2008-2012) and third (2013-2020) trading periods. We find that the market structure is unstable, both in its static and dynamic dimensions, with consequences on prices and supply-side policies. Specifically, trading costs impact firms' trading decisions and static efficiency of the market. Technological progress also alters the effective ceiling over-time by changing plants' baseline emissions.

These results question the benefits of a carbon price floor to remedy these instabilities, by helping market actors anchor expectations about future carbon prices. The market stability reserve implemented in 2019 may indeed create another layer of uncertainty in an already complex regulatory environment. A fourth chapter thus conducts a comparative *ex-ante* analysis of the EU-ETS power sector under the *status quo* or three plausible price floor policies. Our results suggest that no such complementary policies are necessary, because of the MSR's ability to quickly cutback on the number of allowances in circulation. Indeed, our analysis suggests restoring the short-term permit scarcity of permits in decisive in the EU-ETS, where the current excess supply is large.