



Department of Economics and Finance

Chair of Mathematical Finance

**The EU Emissions Trading System and the
Market Stability Reserve mechanism for CO₂
emissions reduction**

SUPERVISOR

Prof. Sara Biagini

CANDIDATE

Francesca Perone Pacifico

245271

ACADEMIC YEAR

2021-2022

Table of contents

Introduction	3
Chapter 1: Pollution as an externality and possible solutions	4
1.1 – Taxes and subsidies	5
1.2 – Command-and-control regulations	6
1.3 – Market oriented tools.....	8
1.3.1 - Emissions fee.....	8
1.3.2 – Cap-and-trade system	10
1.3.3 - Differences in the performance of emissions fees and cap-and-trade	11
Chapter 2: Situation in Europe and European Commission response	14
2.1 – Principal pollutants emitted by industrial activity in Europe	14
2.2 – EEA’s estimation of the pollutants’ marginal and aggregated damage.....	17
2.3 – EU Emission Trading Scheme (EU ETS).....	19
2.3.1 – The EU Emission Trading Scheme’s phases	20
2.3.2 – Functioning of the EU ETS	21
2.3.3 – Auctioning of allowances	23
2.3.4 – Free allocation of allowances	24
2.3.5 – Results and implementations	25
Chapter 3: Model for the EU ETS and the MSR.....	26
3.1 – Model framework for the EU ETS	26
3.1.1 – Competitive intertemporal equilibrium	27
3.1.2 – Equilibrium with rolling horizons	29
3.2 – Model for the MSR.....	30
3.3 – Observations and results.....	32
3.4 – Total Number of Allowances in circulation (TNAC).....	34
Conclusions	36

Introduction

Emissions of green-house gases and other pollutants are one of the main drivers of climate change and create a cost for society due to their negative impact on health and the environment. When these costs are not included in the price of goods produced by polluting companies, a market failure occurs. This is better described in Chapter 1, which analyzes pollution as an externality and provides an overview of possible policies that can be implemented to overcome the market failure generated. Chapter 2 describes more in-depth pollution emissions in Europe and the policy applied by the European Commission (EC) to decrease total emissions. It also illustrates the implementation and the functioning of the EU Emissions Trading System, which is a cap-and-trade mechanism used to distribute and manage emission allowances to installations, with the scope of reducing total pollution to achieve environmental targets. The first phases of the EU ETS were far from perfect due to an overestimation of emissions and the economic recession, which led to a surplus of allowance supply and very low prices. Hence, to improve the system and reduce emissions in a more efficient way, the EC implemented the Market Stability Reserve, which is a reserve of set-aside permits aimed at reducing the imbalances in emissions allowances' supply and demand and increase the flexibility of the EU ETS in responding to unexpected shocks by adjusting the number of permits in the market according to given thresholds. Chapter 3 provides a model for both the EU ETS and the MSR, including the cancellation mechanism which will be activated in 2023. The EU ETS is modeled as a competitive emissions trading system with full banking and limited borrowing of emission permits over time. In this discrete time dynamic model firms make production decisions using rolling finite horizons and limited foresight and choose emissions and abatement by optimizing intertemporal abatement costs. The MSR is modeled as a banking corridor which automatically adjusts current auctions based on banking history. Finally, Chapter 3 also illustrates the results obtained by the EU ETS and the MSR describing the impact on emissions reduction, allowances prices and the impact of the reserve on total allowances in circulation. (TNAC).

Chapter 1: Pollution as an externality and possible solutions

An externality is a benefit or cost that occurs when one entity's activity directly affects the welfare of another in a way that is not reflected in the market price. Externalities, whether positive or negative, reduce market efficiency creating a market failure.

Figure 1 depicts the inefficiency brought about by a negative externality: the horizontal axis represents the amount of output, Q , produced by firms, while the vertical axis measures Euros. For each level of output, the MB curve shows the marginal benefit of production, while the MPC schedule represents the firm's cost. The harm that production causes to society is shown by the MD curve and the MSC curve represents the total marginal social cost, which is the sum of the marginal private cost and the marginal damage, if the externality didn't exist the marginal damage would be null and the MSC would correspond to the MPC .

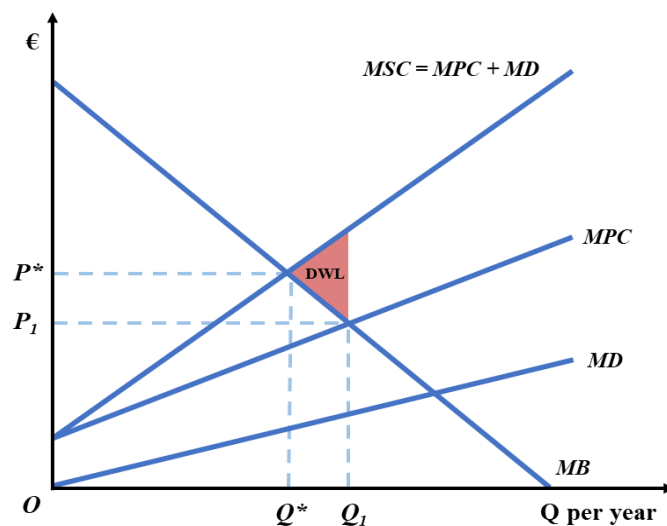


Figure 1

Firms will produce as long as their MB exceeds their MPC , meaning the equilibrium is represented by quantity Q_I . However, from society's standpoint, the optimal output would be Q^* , the intersection of the MSC and the MB curves. When firms fail to consider the MD in deciding how much to produce, the market is inefficient, and a dead weight loss occurs because the quantity produced is in excess and the price is below the optimal.

Production-related pollution has many detrimental effects on society, such as air, water, and soil contamination, as well as the possibility of serious health issues for those who live in contaminated areas. These effects are not represented in the price of the goods produced, meaning that the social cost of production is higher than the private cost of production. At the market output, social costs of production exceed social benefits to consumers, and the market produces too much of the product.

In order to achieve optimal production, firms should be required to take into consideration the social costs of polluting; however, the marginal damage inflicted to society is difficult to estimate.

To address the externality problem and reduce emissions, the government can step in and target either the reduction of output produced, by applying a Pigouvian tax or subsidy, or pollution reduction through command-and-control regulations or market-oriented environmental tools.

1.1 – Taxes and subsidies

A Pigouvian tax is a tax levied on each unit of a polluter’s output in an amount just equal to the marginal damage it inflicts at the efficient level of output, Q^* .

This results in an increase in the firms’ marginal private cost (as depicted in Figure 2) equal to the tax per unit, shifting the MPC curve upwards and achieving the socially efficient output production, since profit-maximization requires businesses to produce the amount for which the marginal benefit is equal to the marginal cost.

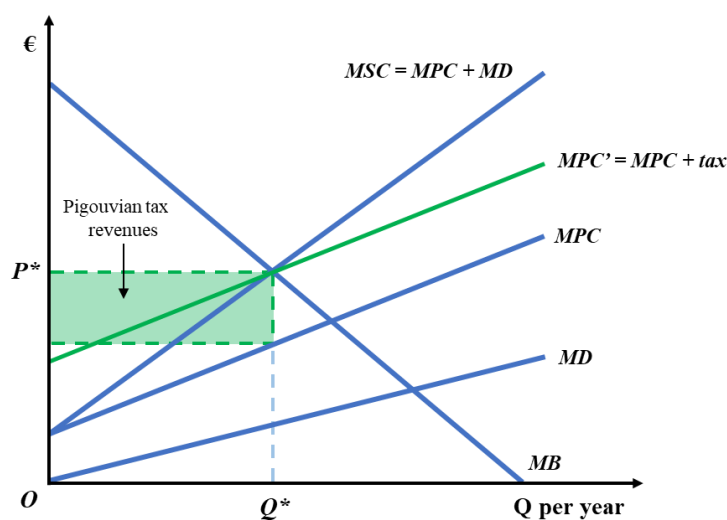


Figure 2

The Pigouvian tax forces firms to consider the costs of the externality they generate and induces them to produce efficiently. Moreover, since the polluters must pay a tax on each of the units produced, this policy generates revenue for the government, represented by the green rectangle in Figure 2.

The main problems with the application of the Pigouvian tax arise from the difficulty in estimating the marginal damage function, making it hard to find the correct tax rate to be applied.

An alternative to the Pigouvian tax is the payment of a subsidy for each unit of output reduced. Assuming a fixed number of polluting firms, the efficient level of output can be achieved by paying the polluters not to pollute. The subsidy works similarly to the tax since it increases the polluter’s effective production cost. If the government pays a subsidy equal to the marginal damage inflicted

at the optimal level of production Q^* , for each unit of output below Q_I , then the firms' cost of producing Q_I becomes the sum of their marginal private costs and the subsidy they would forego by producing.

Therefore, as represented in Figure 3, the MPC curve shifts upwards by the amount of the per unit subsidy and induces firms to produce at the efficient level. In fact, for any unit of production greater than Q^* , it would be inefficient for firms to produce rather than to take the subsidy, while, for quantities lower than Q^* , it would be inefficient to accept the subsidy as the MPC' curve would be below the MB line.

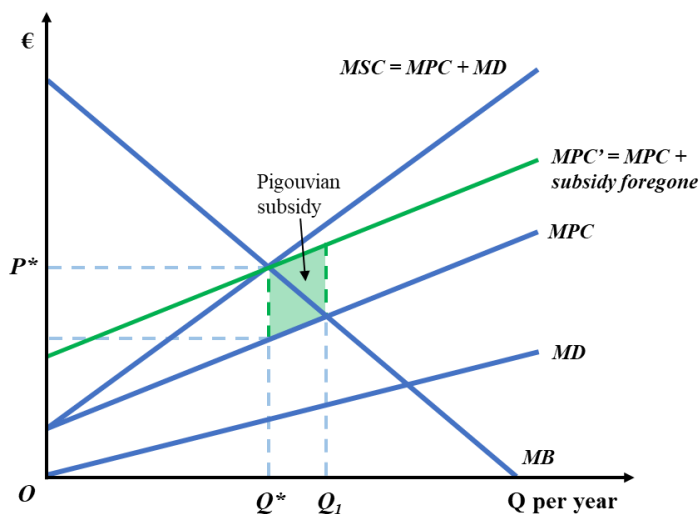


Figure 3

In the case of the subsidy, the government does not have a revenue but a cost, while each firm receives a payment equal to the number of units of foregone production ($Q_I - Q^*$) times the subsidy per unit; the amount received by firms is represented by the green area in Figure 3.

In addition to the marginal damage estimation issues, applying the Pigouvian subsidy could have the opposite result from what is intended. In fact, because the subsidy generates a profit, it may encourage the establishment of new polluting businesses, which would ultimately lead to an increase in pollution rather than a decrease.

1.2 – Command-and-control regulations

Although both the tax and the subsidy may result in a socially efficient outcome, it's possible that neither will encourage businesses to look for alternatives to reducing output, as a means of reducing pollution. The government can implement regulations that are based on the amount of emissions that are cut in order to encourage innovation.

Figure 4 represents the market for pollution reduction, with the firms' annual level of pollution reduction shown on the horizontal axis. The MSB curve represents the benefit gained by society for

each unit of emissions cut, it is downward sloping reflecting the assumption that society becomes worse off, at an increasing rate, for each additional unit of pollution. On the other hand, the *MC* curve represents the costs incurred by firms in reducing emissions, these costs can stem from reducing output, shifting to cleaner inputs, or installing a new technology to control pollution. This curve is assumed to be upward sloping suggesting that the cost to firms to reduce pollution increases at an increasing rate.

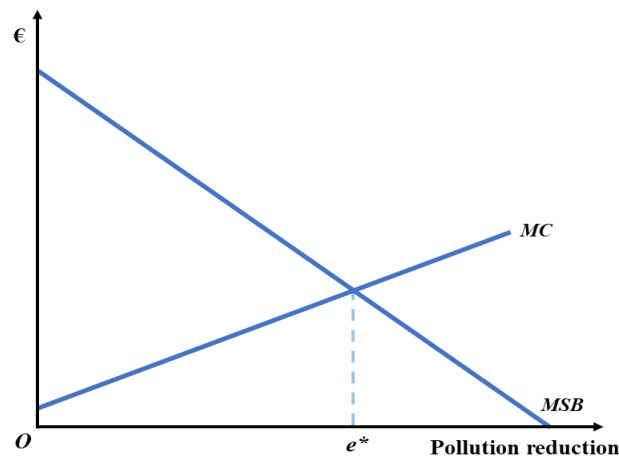


Figure 4

Without any government intervention, there is no incentive for firms to reduce pollution, meaning that the market will be at point *O*, whereas the efficient outcome is obtained when the firms' marginal cost for reducing pollution is equal to the society's marginal social benefit, which occurs at point e^* (see Figure 4). To achieve efficiency, the government can apply, as stated earlier, command-and-control regulations: policies that allow policymakers to specifically regulate both the amount (performance standards) and the process (technology standards) by which a firm should maintain the quality of the environment.

Technology standards require firms to use a particular technology to reduce their emissions; no other technology is permitted. Since this is a cost for production, firms are obliged to take into consideration the social cost of polluting when making production decisions.

On the other hand, performance standards set an emission goal for each producer and allow some flexibility in the process of achieving the target. It is more cost-effective than a technology standard.

Although these policies are effective, there are some issues with these regulations:

First, they offer no incentive to improve the quality of the environment beyond the standard set by these laws. Once the command-and-control regulation has been satisfied, polluters have zero incentive to do better.

Second, they are inflexible. They usually require the same standard for all polluters, as well as the same pollution-control technology. This means that command-and-control regulation draws no

distinctions between firms that would find it easy and inexpensive to meet the pollution standard, or to reduce pollution even more, and firms that might find it difficult and costly to meet the standard. Firms have no motive to rethink their production methods in ways that might reduce pollution even further and at a lower cost.

1.3 – Market oriented tools

Emissions fees and cap-and-trade systems are incentive-based regulations (or market oriented environmental tools) that provide polluters with market incentives to reduce pollution while allowing polluters considerable flexibility in deciding how to reduce emissions and who should reduce them.

1.3.1 - Emissions fee

An emissions fee is a tax imposed on the quantity of pollution that a firm emits, it operates similarly to the Pigouvian tax illustrated earlier, except that it is levied on each unit of pollution rather than each unit of output. A pollution charge gives profit-maximizing firms an incentive to figure out ways to reduce their emissions, as long as their marginal cost is lower than the tax. A company that must pay a pollution tax will be motivated to research the least expensive pollution-reduction technologies. Firms that can reduce pollution cheaply and easily will do so to minimize their pollution taxes, whereas firms that will incur high costs for reducing emissions will end up paying the pollution tax instead.

If the government levies a tax equal to f^* for each unit of pollution (as shown in Figure 5), where f^* is the marginal social benefit of pollution reduction at the efficient level e^* , a polluting firm will incur a cost of MC for each unit of pollution it reduces, however, with the fee in place, its tax bill will go down by f^* for each unit of emission cut. As a result, as long as f^* is greater than the

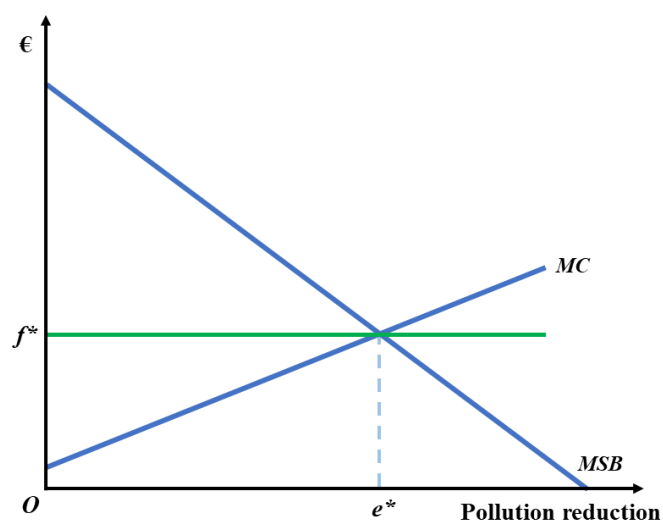


Figure 5

marginal cost ($f^* > MC$), it is convenient for the firm to reduce pollution, achieving the efficient level of pollution reduction e^* ($MC = f^*$).

This outcome could have also been obtained through a command-and-control regulation demanding a cut in pollution of e^* . However, the emission fee has more advantages when there is more than one polluter in the market, as illustrated in the example in Figure 6.

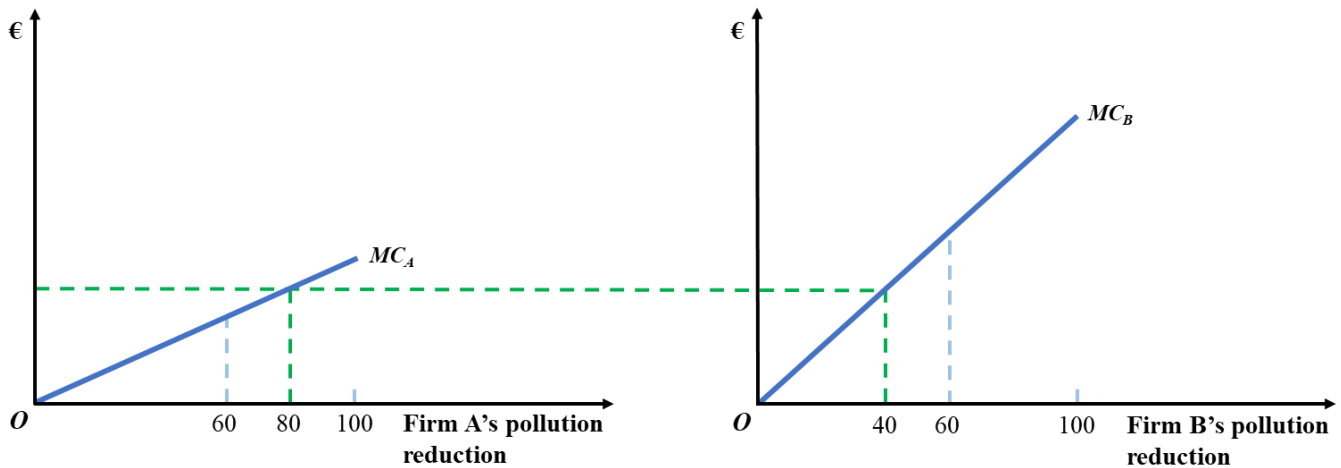


Figure 6

Firms may have different MC curves associated with pollution reduction, in the example in Figure 6 Firm A's MC is lower than Firm B's and both companies initially emit 100 units of pollution per year. Assuming the government estimates an efficient pollution reduction of 120 units per year between them, total pollution must be reduced from 200 to 80 units per year. If the government decides to apply a performance standard demanding a reduction of 60 units per year each, the desired reduction would be achieved but at a higher cost than necessary. In fact, looking at Figure 6, it can be noticed that the Firm B's marginal cost of reducing the 60th unit is higher than Firm A's ($MC_B > MC_A$). Firm A could cut pollution by one more unit instead of Firm B, lowering overall costs. In sum, as long as the marginal costs of the two polluters differ, the burden can be redistributed so that the total cost falls. The total cost of emissions reduction is minimized only when the marginal costs are equal across all polluters. In the example the cost-effective means of achieving the 120-unit reduction is for Firm A to cut its pollution by 80 units and for Firm B to reduce its by 40 units.

The emissions fee achieves the cost-effective outcome while rewarding those who cut more emissions. This is represented in Figure 7, which shows the same curves as Figure 6 with the addition of an emission fee, f' . As previously stated, when there is an emission fee, the polluter will cut back on pollution until its marginal cost equals the fee. It is cost-effective because all polluters pay the same fee, which leads to equal marginal costs for all polluters. Both firms will have to pay the tax on the units of pollution they emit, so in the example shown in Figure 7, Firm A will pay the

fee on 20 units while Firm B will have to pay taxes on 60 units. The company that reduces pollution the least will face a higher tax liability than the company that reduces pollution the most.

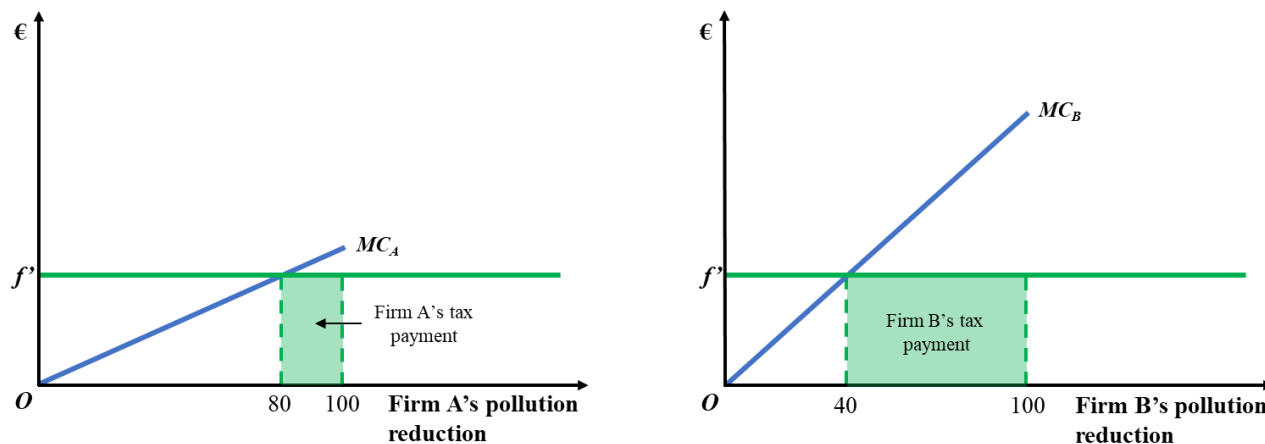


Figure 7

The main benefit of an emission fee because that because it reduces pollution at the lowest possible cost because the marginal costs of polluters will always be equal for any fee; changing the amount of the tax will change the number of total emissions reduced.

1.3.2 – Cap-and-trade system

As an alternative policy to the emission fee, the government can institute a system of tradable pollution permits, known as cap-and-trade, a program in which a city or state government issues permits allowing only a certain quantity of pollution. These permits to pollute can be sold or given to firms for free and can be then traded among firms. When establishing the program, the government must first determine the overall amount of pollution it will allow, to meet national pollution standards. The firms that emit that pollutant are then given a number of permits that allow only that amount of emissions. As long as permits are tradable, from an efficiency standpoint, their initial allocation among the polluters does not matter, the outcome will be cost-effective regardless, this is represented in the example in Figure 8, which replicates the marginal cost curves of Figure 6.

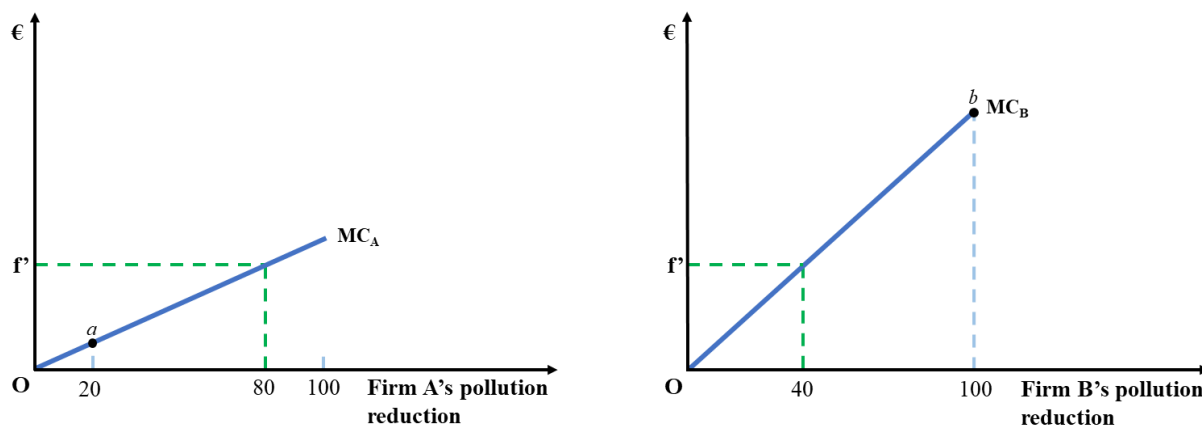


Figure 8

Assuming that the government wants to reduce pollution to 80 units per year, it will issue 80 permits (assuming one permit per unit). If they are all allocated to Firm A, then Firm A will only have to reduce annual pollution by 20 units (point *a*), while Firm B will have to cut its emissions completely, eliminating 100 units (point *b*). In this situation $MC_B > MC_A$ so total costs are higher than needed. When trading of permits is allowed, Firm A will be willing to sell a permit as long as the amount it receives is higher than its marginal cost of reducing one more unit of emissions, and Firm B will be willing to buy the permit as long as its cost is lower than the savings it obtains by polluting one more unit. Therefore, the permits will be traded until $MC_A = MC_B$, which is the cost-effective outcome.

No matter how the government initially distributes the permits to the businesses, pollution would be reduced in the same way; however, initial allocation does affect the income distribution, both firms would prefer to be the seller rather than the buyer.

1.3.3 - Differences in the performance of emissions fees and cap-and-trade

Emission fees and cap and trade programs are symmetrical policies, it is indeed interesting to notice that at the equilibrium point in Figure 8 the price of the permits will be equal to the emission fee seen earlier in Figure 7. For every emissions fee, in theory, there is a cap-and-trade system that achieves the same outcome, and vice versa. However, in practice there are some differences in how the two systems perform.

Firstly, if the economy is experiencing inflation, the real emissions fee will fall, leading to less pollution reduction, if not adjusted, while the cap-and-trade system leads to the same amount of pollution regardless of inflation.

Secondly, when firms' marginal costs for reducing emissions change, the emission fee causes pollution reduction to decline as marginal costs rise because it sets a ceiling and allows businesses with higher costs to pay the tax rather than reducing pollution by an additional unit. On the other hand, cap and trade system sets a strict limit on pollution, which does not vary as economic conditions change, however the cost of achieving the pollution reduction target can become very high if marginal costs increase.

In sum, an emission fee limits the cost of reducing pollution but leads to changes in emissions as economic circumstances change, whereas a cap-and-trade system limits the number of emissions but leads to changes in the cost of reducing pollution as the economy changes.

One interesting option is to combine the cap-and-trade system with the emissions fee. In this hybrid approach the government sets up a cap-and-trade system that fixes the amount of allowable pollution. However, the government also makes it known that it will sell as many additional permits

as are demanded at a pre-established price. The price, known as the safety valve price, can be set rather high so it will only be used if the cost of pollution reduction is much higher than expected. In effect the safety valve relaxes the pollution cap if the marginal cost of reduction increases beyond a level that policymakers deem acceptable.

The two policies differ also in response to uncertainty, depending on whether the marginal social benefit of reducing pollution is inelastic or elastic. With an inelastic schedule, the first units of pollution reduction are highly valuable, but as more reductions occur, their incremental benefit falls off rapidly. With an elastic schedule, the marginal value of each unit of pollution reduction remains fairly constant. In both cases when marginal costs are higher than expected, neither emissions fees nor cap-and-trade system are perfectly efficient, as the emissions fee achieves too little pollution reduction while cap-and-trade achieves too much. The two instances are represented respectively in Figure 9 and Figure 10.

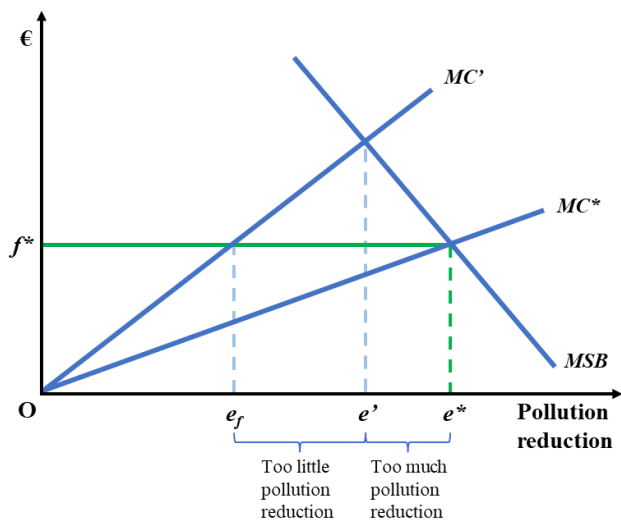


Figure 9

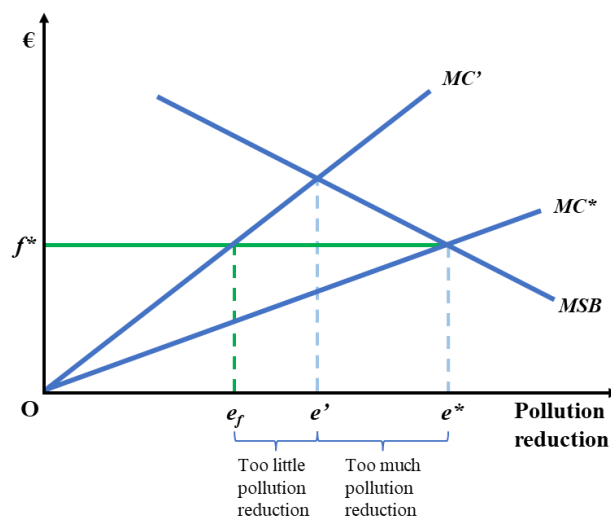


Figure 10

In the graphs above, MC^* represents the government's best guess of the marginal cost schedule which, due to uncertainty, could actually be as high as MC' . Relying on the best guess estimate on MC^* the government would set an emission fee of f^* or would emit enough permits to achieve e^* units of pollution reduction. However, in the instance in which the real marginal cost curve is MC' , the efficient outcome would be e' . Cap and trade would reduce pollution more than the efficient approach because the level of pollution reduction is constant regardless of the circumstance, whereas the emissions fee would reduce pollution less as the new equilibrium would be e_f , the point where the government-set emission fee intersects with the new marginal cost, MC' . When the MSB curve is inelastic, the cap-and-trade system yields results that are closer to the efficient outcome than the emissions fee system (as shown in Figure 9).

When the *MSB* curve is elastic and costs are higher than expected, as represented in Figure 10, the emissions fee achieves an amount that is closer to the efficient one relative to the cap-and-trade system outcome, making it the preferred option.

Finally, there are differences in the distributional effects of emission fees and cap and trade. With an emissions fee, the government receives funds from taxes that polluters pay for each unit of pollution. In a cap-and-trade system, if the permits are provided directly and without charge to the polluting companies, the government does not profit from it, but, if the government sells permits to polluters as opposed to giving them away for free, it can generate a revenue.

Under certain circumstances, a command-and-control approach is preferable to an incentive-based system, as the latter is possible only if emissions can be monitored. If it is impossible or very expensive to keep track of emissions, the government won't be able to charge a per-unit emission fee or establish whether a polluter has enough allowances to cover its emissions. Another potential problem with incentive-based regulations is that they can lead to high concentrations of pollution in certain local areas ("hot spots"). A command-and-control regulation can avoid this by restricting emissions from each individual pollution source.

The advantage of market-oriented environmental tools is that they can achieve any desired reduction in pollution at a lower cost to society than command-and-control regulation.

Chapter 2: Situation in Europe and European Commission response

As stated in Chapter 1 pollution is an externality that has detrimental consequences for society, which can be divided into economic, social and environmental costs.

Economic costs include a wide range of externalities such as property and infrastructure damage, as well as decreased productivity of people and crops. Acid rain (and deposition), smog, and ozone pollution alter the time scale over which investments in infrastructure can be amortized, their maintenance, and replacement. In addition to health costs, air pollution has a direct impact on labor productivity force in terms of total people-hours lost due to time spent at home, in health facilities, or caring for others. Air pollutants also have a direct impact on crops and timber products, so losses may be expected in their yield.

Regarding social costs, almost all air pollutants have physiological effects on humans, primarily but not exclusively on the cardiovascular and respiratory systems. Some effects are obvious and direct whereas others are far more pernicious and indirect. As a result, the social costs associated with air pollution stem principally from increased medical costs and the reduction of life expectancy due to the exposure to emissions.

Environmental costs include general damage done to ecosystems, except for what may be considered economically useful to human activities (like crops). Environmental costs are the most difficult to assess in a comprehensive manner since they include damages to biological diversity and sustainability.

2.1 – Principal pollutants emitted by industrial activity in Europe

To establish the monetary damage of the externality caused by European firms, the European Environment Agency (EEA) in 2021 redacted a report¹ assessing in monetary terms marginal damage costs (damage cost per ton of pollutant emitted) and total costs of damage to health and the environment caused by air pollutant emissions from industrial facilities officially reported to the European Pollutant Release and Transfer Register (E-PRTR)², from 2008 to 2017.

The air pollutants included in the EEA study are divided into four main groups:

- Main air pollutants: particulate matter (PM_{2.5}, PM₁₀), Sulphur dioxide (SO₂), ammonia (NH₃), nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOCs);
- Heavy metals: arsenic, cadmium, chromium VI, lead, mercury, nickel;

¹ ETC/ATNI Report 04/2020: Costs of air pollution from European industrial facilities 2008–2017.

² The E-PRTR registers data from industrial facilities located in the EU-27 countries plus Iceland, Liechtenstein, Norway, Switzerland, Serbia and the UK.

- Organic pollutants: 1,3 butadiene, benzene, formaldehyde, benzo(a)pyrene, dioxins and furans;
- Greenhouse gases: carbon dioxide (CO₂), methane and nitrous oxide.

Nitrogen oxides are a byproduct of fuel combustion, for instance from power plants and other industrial facilities. NO_x contributes to water and soil acidification and eutrophication³ and can lead to the formation of particulate matter and ground-level ozone. The most adverse effects on health are caused by the NO₂, chemical specie that comprise NO_x; high concentrations can cause airway inflammation and reduced lung function.

Sulphur dioxide is emitted when sulfur-containing fuels are burned. SO₂ contributes to acidification, with potentially serious consequences including adverse effects on aquatic ecosystems in rivers and lakes, and damage to forests. High levels of SO₂ can impair airway function and inflame the respiratory tract. Moreover, SO₂ contributes also to the formation of particulate matter in the atmosphere.

Ammonia contributes to both eutrophication and acidification. Around 93% of NH₃ emissions in Europe are attributable to the agricultural sector while a relatively small amount is released from various industrial processes, transportation, and waste management.

NMVOCs, important ground-level ozone precursors, are emitted from many sources including industry, paint application, road transport, dry-cleaning and other solvent uses. Certain NMVOC species, such as benzene (C₆H₆) and 1,3-butadiene, are directly hazardous to human health.

PM is one of the most significant pollutants when it comes to the possibility of endangering human health because it can enter vulnerable areas of the respiratory system and aggravate or cause cardiovascular, lung, and cancerous conditions. PM is emitted from many sources and is a complex mixture comprising of both primary and secondary PM; Primary PM is the portion released directly into the atmosphere, whereas secondary PM forms in the atmosphere after the release of precursor gases (mainly SO₂, NO_x, NH₃ and some NMVOCs).

The heavy metals arsenic (As), cadmium (Cd), chromium (Cr) lead (Pb), mercury (Hg) and nickel (Ni) are mainly emitted as a result of various combustion processes and from industrial activities. In addition to polluting the air, heavy metals can be deposited on terrestrial or water surfaces and

³A process of pollution that occurs when a lake or stream becomes over-rich in plant nutrient; it leads to an overgrowth of algae and other aquatic plants. When these plants die and decompose, they rob the water of oxygen and the lake, river or stream becomes lifeless.

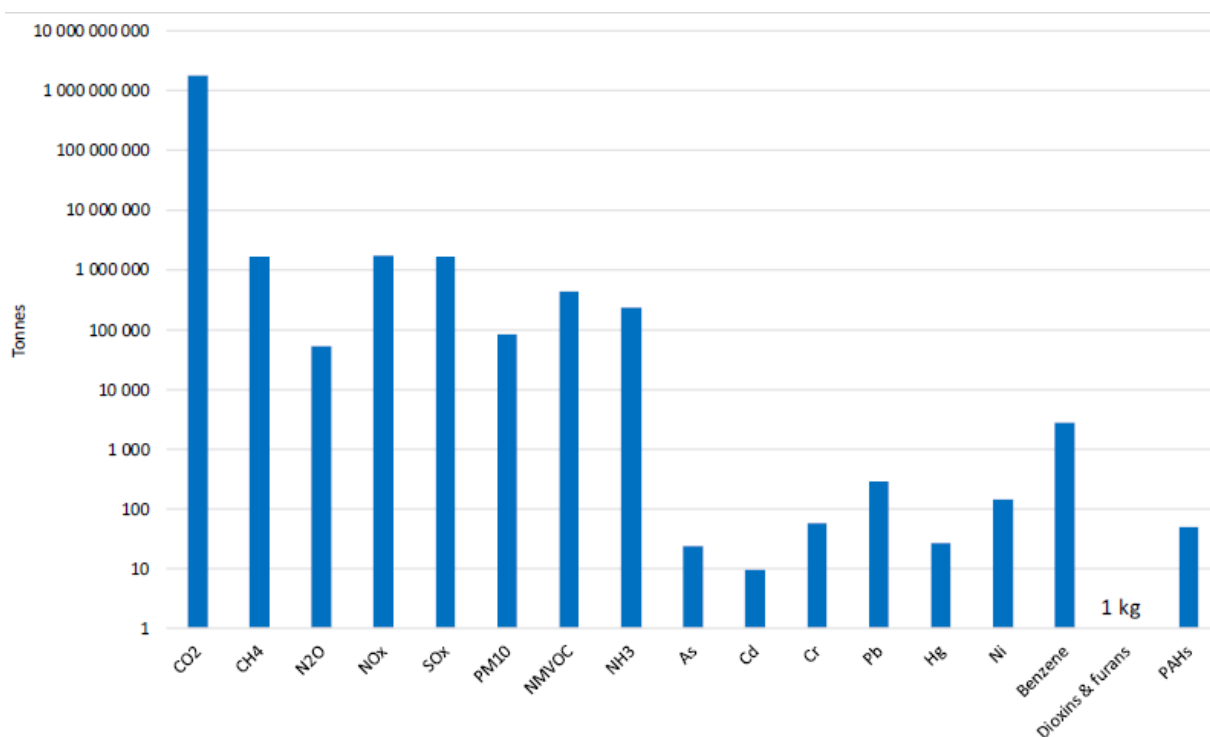
subsequently build up in soils and sediments. Heavy metals can also build up in food chains. They are usually harmful to both terrestrial and aquatic ecosystems.

Organic pollutants include benzene, polycyclic aromatic hydrocarbons (PAHs), dioxins, and furans. They each have different negative effects on human health and ecosystems, and each is a known or suspected human carcinogen. Dioxins, furans, and PAHs bioaccumulate in the environment as well. These substances are commonly emitted during the combustion of fuels and wastes, as well as during various industrial processes.

Carbon dioxide is emitted when fuels such as coal, oil, natural gas, and biomass are burned for industrial, domestic, and transportation purposes. CO₂ is the most significant greenhouse gas influencing climate change, thereby posing a threat to public health and the environment.

An estimate of the volume and distribution of the pollutants described above, in Europe, is provided in Figure 11⁴, which illustrates the emissions of each pollutant reported to the E-PRTR in 2017. CO₂ dominates emissions, followed by methane and the main air pollutants and heavy metals. The reported dioxin and furan emissions are so small that they are not visible in the graph.

Figure 11: Emissions reported to E-PRTR in 2017 (logarithmic scale)



⁴Source: ETC/ATNI Report 04/2020: Costs of air pollution from European industrial facilities 2008–2017

2.2 – EEA’s estimation of the pollutants’ marginal and aggregated damage

The marginal damage costs of the main air pollutants have been calculated for impacts on health (from ozone, fine particulate matter, and nitrogen dioxide), on crops and forests (from ozone), on building materials (from Sulphur dioxide and nitrogen oxides) and ecosystems (from eutrophication due to ammonia and nitrogen oxides). Marginal damage costs for impacts on health have been calculated also for heavy metals and organic pollutants. Impacts of greenhouse gases are accounted for using a marginal abatement cost approach that consists in the direct monetization of emissions using the marginal costs of greenhouse gas abatement. The logic behind this approach is partly based on the assumption that climate damage will be prevented by legislation to curb emissions. Under this assumption, an increase in emissions from one source would need to be countered by a reduction in another to the extent that overall emissions would remain at the legislated level and hence there would be no net impact from these changes on climate: the only change in cost would then relate to the costs of controlling emissions.

In the EEA report, the values used for estimating GHGs costs are the ones used in the DG Move Transport Cost Handbook (EC, 2019) which are based on the avoidance cost approach. Avoidance costs are assessed as the costs necessary to reach the objective of the Paris agreement, i.e. to limit the global temperature rise to 1.5 – 2 °C, a level above which substantial climate change is foreseen. This implies a target of 80 – 95 % reduction in CO₂ emissions by 2050 compared to 1990 levels. Based on a literature review, the EEA’s study concludes on the possible avoidance costs presented in Table 1, which are the average of the values found in the literature, calculated for the minimum, maximum and central estimates. The preferred value for the European Commission (EC (2019)) is the central estimate.

Table 1: Climate change avoidance costs in €/tCO₂ equivalent (€₂₀₁₉)⁵

	Low	Central	High
Short and medium term, to 2030	63	105	199
Longer term (2040 to 2060)	164	283	524

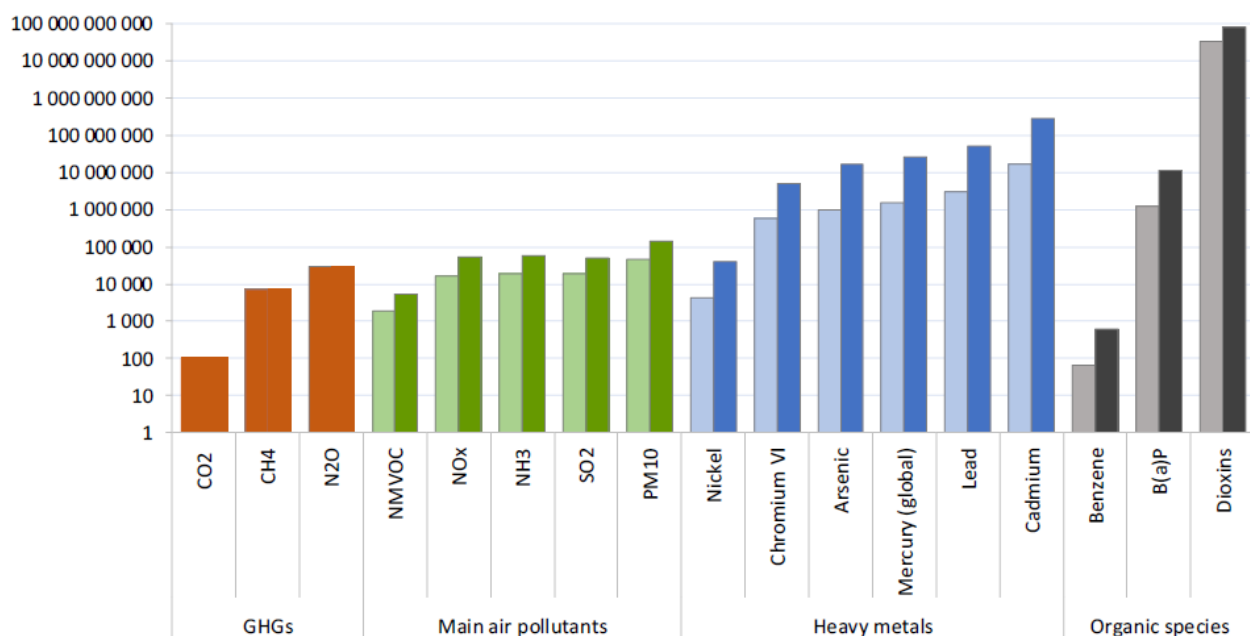
Estimates of average damage cost per ton emitted for all air pollutants are illustrated in Figure 12, which shows the damage costs per unit of emission between pollutants, averaged across countries, except for mercury and CO₂ for which worldwide estimates are shown. It summarizes the MDCs for all the pollutants considered. For ‘main’ regulatory air pollutants, heavy metals and organic pollutants, the figure presents lower and upper bounds of damage costs per ton emitted.

⁵ Source: ETC/ATNI Report 04/2020: Costs of air pollution from European industrial facilities 2008–2017

For the main air pollutants, damage costs are expressed as a range, corresponding to the use of two contrasting but complementary approaches for valuing health damage. The lower values relate to the approach accounting for the value of a life year (VOLY), an estimate of damage costs based upon the loss of life expectancy (expressed as potential years of life lost, or YOLLs). This measure accounts for the age at which deaths occur by giving greater weight to deaths at younger age and lower weight to deaths at older age. Meanwhile, the higher values relate to the approach that calculates damage costs using the value of statistical life (VSL), which is a measure of how much people are willing to pay to reduce their risk of dying from adverse health conditions.

For heavy metals and organic species, however, the low and high damage costs refer to confidence intervals.

Figure 12: Estimates of average damage cost per ton emitted for all air pollutants considered in € (€₂₀₁₉)⁶



The set of marginal damage costs illustrated is used to quantify the impacts and associated damage costs caused by the industrial facilities reporting their emission releases to the E-PRTR.

Table 2 summarizes the aggregated costs over the period 2008-2017 caused by emissions reported from the E-PRTR industrial establishments.

⁶ Source: ETC/ATNI Report 04/2020: Costs of air pollution from European industrial facilities 2008–2017

Table 2: Aggregated damage costs for E-PRTR facilities by pollutant groups from 2008 to 2017 (million €₂₀₁₉)⁷

Aggregated damage costs (million € ₂₀₁₉)										
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Main air pollutants (NH ₃ , NO _x , PM ₁₀ , SO ₂ , NMVOCs)	148 983-483 692	127 559-413 532	118 781-385 673	117 029-379 726	111 144-360 979	98 069-319 434	88 629-288 937	82 838-270 272	70 896-232 313	68 165-223 350
Greenhouse gases (CO ₂ , CH ₄ , N ₂ O)	244 550	224 766	233 786	221 439	220 081	212 972	206 588	202 595	196 725	197 269
Heavy metals (As, Cd, Cr, Hg, Ni, Pb)	20 770	13 414	16 447	13 090	13 133	12 127	12 068	10 547	11 989	11 775
Organic pollutants (benzene, dioxins and furans, PAHs)	339	163	191	191	112	133	129	144	144	137
Sum	414 641-749 350	365 904-651 876	369 205-636 098	351 750-614 446	344 469-594 304	323 302-544 667	307 415-507 723	296 125-483 559	279 753-441 170	277 346-432 532

As shown in Table 2, the aggregated cost of damage over the period 2008–2017 caused by emissions reported from E-PRTR industrial facilities is estimated to amount to a range from 415 to 749 billion € (€₂₀₁₉) in 2008 and from 277 to 433 billion € (€₂₀₁₉) in 2017. Estimated damage has thus decreased over the period. Damage costs from the main air pollutants are reduced by 54 % in 2017 relative to 2008. The reductions for damage from greenhouse gases, heavy metals and organic pollutants, respectively, are 19 %, 43 % and 60 %. In the same period, the number of reporting facilities has remained relatively stable (11,137 in 2008 and 11,893 in 2017). Most of the quantified damage cost is caused by emissions of greenhouse gases and the main air pollutants. Damage cost estimates associated with heavy metal emissions and organic pollutants are significantly lower, but nevertheless contribute several millions of euros harm to health and the environment.

When interpreting the results, it must be kept in mind that reporting to E-PRTR is required only by industrial facilities with an activity rate exceeding a defined threshold and emissions exceeding the pollutant-specific thresholds⁸. Moreover, it is important to observe that the damage estimated in Table 2 represent only the aggregate damage cost caused by industrial facilities and not the overall total damage caused by total emissions from the studied countries that is far higher since it would take into consideration also emissions arising from other activities such as agriculture and transport.

2.3 – EU Emission Trading Scheme (EU ETS)

As previously stated, greenhouse gases, including CO₂, methane (CH₄), and N₂O, are considered to be the primary causes of climate change. Although they are produced from a variety of sources, the main drivers of increased levels of greenhouse gases in the atmosphere are combustion and

⁷ Source: ETC/ATNI Report 04/2020: Costs of air pollution from European industrial facilities 2008–2017

⁸ Specified in the Annex II of the E-PRTR Regulation (Regulation (EC) No 166/2006).

deforestation. Expected consequences of climate change are glacier melting, droughts, changes in precipitation patterns, increased storm intensity, greater flooding, decreased agricultural yield, species extinction, and spread of infectious diseases. These effects will have substantial adverse consequences from an economic and social perspective. Climate change is a typical negative externality problem, thus, economic tools designed to tackle negative externality problems can be utilized, such as well-designed Pigouvian taxes and/or cap-and-trade systems.

To deal with the issue of climate change, the United Nations Framework Convention on Climate Change (UNFCCC) has tried to create a global system to reduce emissions via the Kyoto Protocol, which was implemented in 2005.

The Kyoto Protocol, signed in 1997, established legally binding GHG reduction targets, or caps, for 37 industrialized countries for the first commitment period (2008–2012). As a result, policy instruments to meet the Kyoto commitments became necessary. In March 2000, the European Commission issued a green paper titled "Greenhouse gas emissions trading within the European Union," which included preliminary ideas for the EU ETS design. The EU Emissions Trading Scheme was finally implemented in 2005.

2.3.1 – The EU Emission Trading Scheme's phases

The EU ETS has undergone significant changes since it was put into effect in 2005. After three phases, the fourth was launched in 2021 and will last until 2030.

The first phase of the EU ETS ran from 2005 to 2007 and was seen as the pilot phase. It was used to test price formation in the carbon market and to establish the necessary infrastructure for monitoring, reporting and verification of emissions. The primary purpose of phase 1 was to ensure the EU ETS functioned effectively ahead of 2008, to allow the EU Member States to meet their commitments under the Kyoto Protocol. During this phase the EU cap was set by summing up the separate national caps set by each of the member states (with the oversight of the European Commission), the National Allocation Plans (NAPs). These early NAPs were extremely problematic as they were based on conservative emissions estimates and allocated most allowances for free or based on coal benchmarks for the power sector, thereby incentivizing the most polluting technology. Moreover, the Linking Directive⁹ allowed installations within the EU ETS to use certain emission reduction units generated under the Kyoto Protocol clean development mechanism (CDM) to meet their obligations under the EU ETS. Consequently, the resulting cap was so large

⁹ Linking Directive (2004/101/EC). It establishes a link between the European Union Greenhouse Gas Emission Trading Scheme (EU ETS) and the project-based mechanisms of the Kyoto Protocol to the United Nations Framework Convention on Climate Change.

that the total number of allowances issued actually exceeded the emissions of the covered sectors in 2006, which caused the price of allowances to fall to zero. Fortunately, this oversupply was only a temporary issue since Phase 1 credits could not be transferred over to Phase 2.

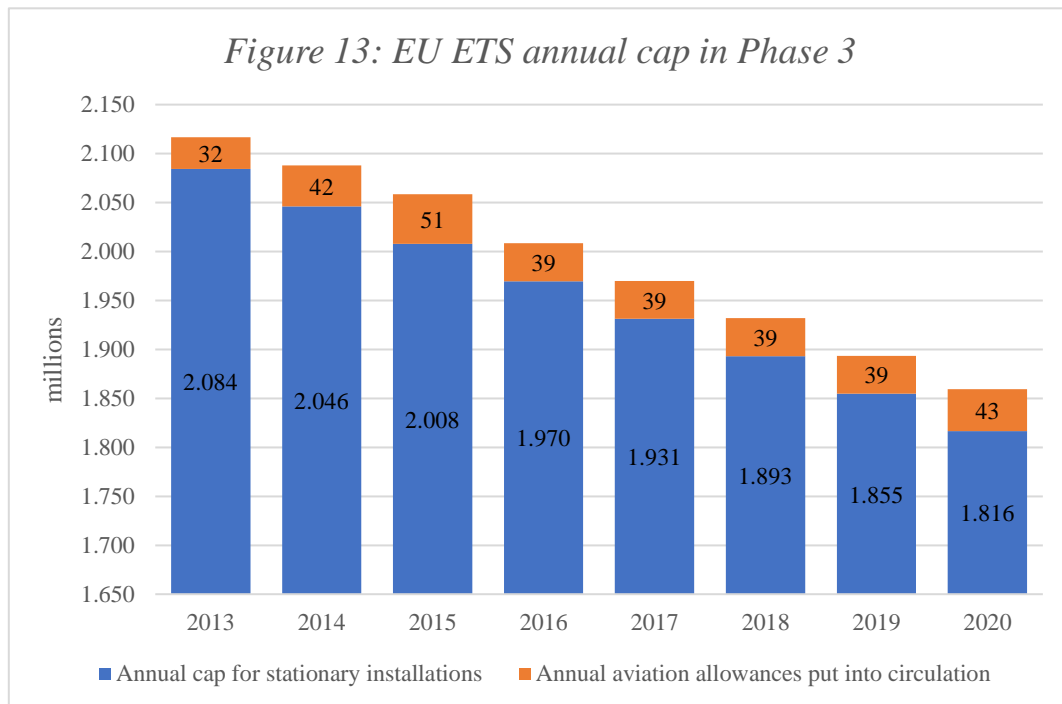
The second phase ran from 2008 to 2012, coinciding with the first commitment period under the Kyoto Protocol. Phase 2 continued the use of the NAPs but with a lower overall cap based on actual emissions data from the first phase. In this phase the Linking Directive was extended also to the use of emission reduction units generated under the Joint Implementation (JI) to fulfill their obligations under the EU ETS. This made the EU ETS the largest source of demand for CDM and JI emission reduction units. The combination of these international credits with an overgenerous cap and the effects of the financial crisis of that period (lower economic output decreased emissions while allowances' supply was not adjusted) led to an enormous oversupply keeping permits prices down. Towards the end of phase 2 the scope of the EU ETS was expanded by including aviation from 2012.

The lessons learned from the previous two phases shaped the third phase of the EU ETS. Following a review of the EU ETS agreed upon in 2008, significant efforts were made to improve scheme harmonization across the EU. Phase 3 ran from 2013 to 2020, coinciding with the Kyoto Protocol second commitment period, as agreed in Doha in December 2012. In this phase, more sectors and greenhouse gases were included. Moreover, instead of the NAPs, a single EU-wide cap on emissions was established. Allowances were mostly distributed through auctions, and the energy sector no longer received free permits, apart for few exceptions. The use of international credits was still allowed but only for far smaller quantities (around 500 million in Phase 3 compared with over a billion in Phase 2) and they had to be exchanged for EU allowances (EUAs) reducing the problem of oversupply. However, these international permits continued to undermine the carbon price on the ETS as they were significantly cheaper than EUAs.

2.3.2 – Functioning of the EU ETS

The EU ETS operates in all EU countries plus Iceland, Liechtenstein and Norway and limits emissions from more than 10.000 installations in the power sector and manufacturing industry, as well as airlines operating between these countries. The EU ETS is a cap-and-trade system under which allowances of greenhouse gas emissions are traded. One permit gives the right to emit one ton of CO₂ equivalent (CO₂e). The cap is the maximum absolute quantity of GHG emissions that may be emitted by entities covered by the EU ETS to ensure the ETS emissions reduction target is

met. A common EU-wide cap applies for the entire EU ETS. Figure 13¹⁰ illustrates the total annual caps in Phase 3 (sum of annual cap for stationary installations and annual aviation allowances).



The cap is designed to decrease annually, reducing the number of allowances available to businesses. During phase 3 the cap decreased every year by the linear reduction factor of 1.74% (about 38 MtCO₂e per year), ensuring that total emissions fell. In phase 4, the cap for both stationary installations and aviation decreases annually by the linear reduction factor of 2.2% (about 48 MtCO₂e per year). Each year allowances are distributed among industries of the various Member States, a proportion of the allowances are given to certain participants for free (for example in sectors where carbon leakage is considered to be a potential risk), while the rest are sold, mostly through auctions. At the end of the year the participants must return an allowance for every ton of CO₂e they emit. If a participant has insufficient allowances, then it must either take measures to reduce its emissions or buy more allowances in the market. Participants can acquire allowances at auction, or from each other. Participants can also decide to bank allowances for use in later years. The prices of allowances are determined in the free market by demand and supply. Compliance to the cap is ensured through the penalty and enforcement structure. Significant fines are imposed if companies fail to comply by surrendering sufficient allowances in time (set at €100/tCO₂ and rising with EU inflation from 2013). In addition, firms face an obligation to surrender the allowances owed. Thus, the target is maintained effectively.

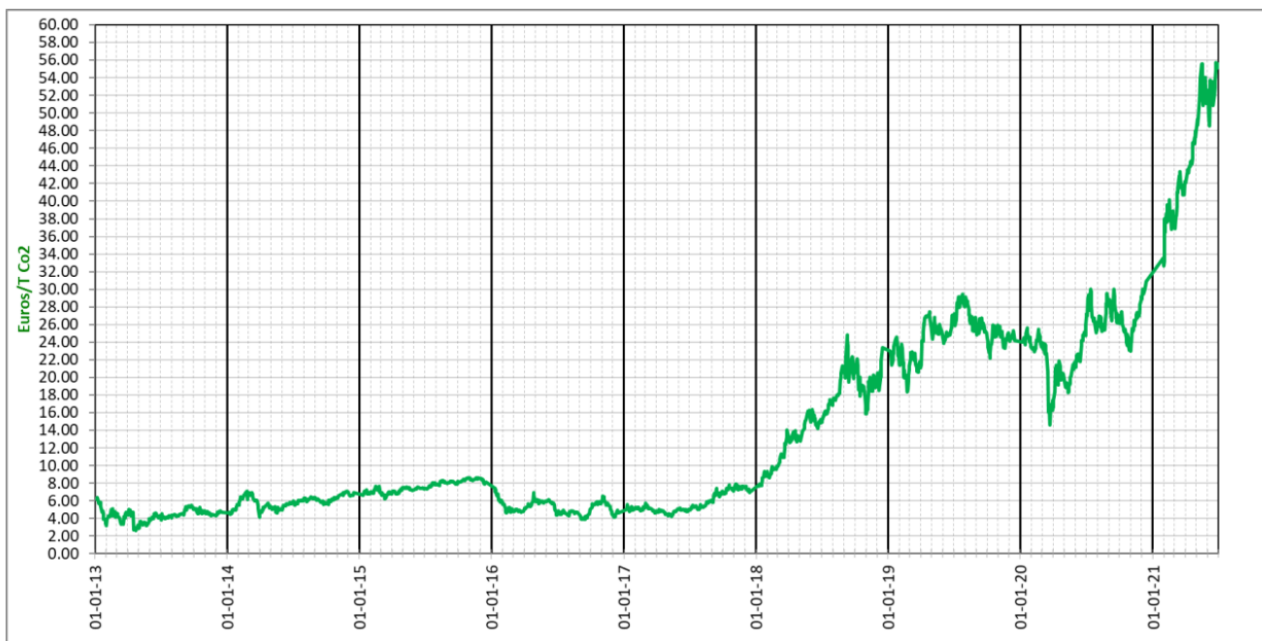
¹⁰ Source EEX

2.3.3 – Auctioning of allowances

As of phase 3, auctioning¹¹ is the primary method of distributing allowances in the EU ETS, accounting for 57% of the total volume (reaching, in 2017, a peak of total auction volume of more than 955 million between general and aviation allowances)¹².

The auction format is a single-round, sealed bid and uniform-price auction. This simple auction format facilitates participation by all authorized bidders, including SMEs. During a single bidding window, bidders can submit, modify and withdraw any number of bids with a lot size of 500 or 1000 allowances, depending on the auction platform. Each bid must specify the number of allowances the bidder wishes to purchase at a given price. Directly following the closure of the bidding window, the auction platform will determine and publish the clearing price, price at which the sum of volumes bid matches or exceeds the volume of allowances auctioned (the trend of clearing prices from 2013 to 2021 is shown in Figure 14).

Figure 14: Clearing prices for auctions of general allowances (January 2013 - 30 June 2021)



Source: EEX

All bids higher than the clearing price are successful. These bids are sorted by price, and bid volumes are allocated beginning with the highest bid. A random selection algorithm is used to sort tied bids. For each auction, if the volume is not auctioned off completely, the auction is cancelled.

¹¹ Governed by the Commission Regulation (EU) 1031/201033 (Auctioning Regulation), which specifies the timing, administration, and other aspects of how auctions should take place to ensure an open, transparent, harmonized, and non-discriminatory process.

¹² Source EEX

This occurs when the bidding volume is less than the available volume for auction, or when the clearing price is less than the auction reserve price. This reserve price is a secret minimum clearing price set by the auction platform prior to the auction in close consultation with the auction monitor, and it's based on the prevailing market price for emission allowances before and during the close of the bidding window. Allowing a clearing price significantly under the market price could distort the carbon price signal, disturb the carbon market and would not ensure that bidders pay fair value for the allowances. In such a case, the auction is canceled. The auctioned volume will then be distributed evenly across the next auctions scheduled on the same auction platform.

The proceeds from auctions are distributed to Member States, who can decide how to use them in accordance with the EU ETS Directive, following which, 50% of revenues should be used for climate and energy-related purposes; this is a non-binding recommendation that member states may choose to ignore. They must, however, report on their revenue use.

The total revenues generated by Member States, the UK and Iceland, Liechtenstein and Norway from the auctions in phase 3 exceeded 68 billion euros (with over €19 billion in 2020 alone and nearly €14 billion euros in the first half of 2021).

According to the information submitted by Member States to the Commission, it is estimated that around 75% (€56.5 billion) of total revenues throughout phase 3 was used for climate and energy purposes, with the majority spent on domestic renewable energy, energy efficiency, and research and development.

2.3.4 – Free allocation of allowances

The free allocation of permits is used in the case of carbon leak risk, meaning the risk that the company would shift production to a country with less stringent policies on carbon emissions, that would lead to an increase of total pollution. Free-allocated permits are distributed using a benchmarking approach, which allocates allowances based on the emission intensity of a firm's production in comparison to other installations in the same sector. GHG-intensive installations will receive fewer free allowances in relation to their production than highly efficient installations, forcing inefficient installations to take action to offset their excess emissions.

The use of free allocation cuts the cost of compliance for industries, and safeguards capital that can be used to invest in emissions reductions and energy efficiency. Reducing the costs of the EU ETS to participants is especially important if other developed countries and major emitters of greenhouse gases do not take comparable action to reduce GHG emissions. In that case, certain energy-intensive sectors in the EU that compete on a global scale could be put at an economic disadvantage. Free allocation can mitigate this potential drawback.

Since the marginal gain from lowering GHG emissions is derived directly from the carbon price, free allocation has no effect on it in theory. In practice, however, free allocation may still have an impact on the incentive because less capital is required to comply with the EU ETS. The cash costs of purchasing allowances or investing in mitigation measures are no longer present when permits are distributed for free, limiting the urgency to reduce emissions. As a result, excessive free allocation, or even overallocation, may reduce the incentive to abate, even if the marginal gain remains. Free allocation can result in windfall profits for industries that pass on some or all of the cost of allowances to their customers, since the cost of allowances is considered by firms when making production and pricing decisions.

2.3.5 – Results and implementations

Since the EU ETS was launched in 2005, emissions in the power and heat generation as well as energy-intensive industrial sectors covered have fallen by around 43%, with a reduction of emissions in phase 3 of almost 29%. Together with other legislation, such as on renewable energy and energy efficiency, it has contributed significantly to achieving the EU's overall target of reducing GHG emissions by 20% by 2020 from 1990 levels. The EU surpassed this target and reduced GHG emissions by approximately 31% below 1990 levels in 2020.

As mentioned before, since 2008 the EU ETS has accumulated a large and unsustainable oversupply and, at the start of phase 3, it had a high structural imbalance between the supply and demand of allowances, equaling 2.1 billion allowances. To address this imbalance the European Commission in 2014 postponed the auctioning of 900 million allowances from 2014, 2015, and 2016 to 2019-2020 (as a short-term solution) and created the Market Stability Reserve (MSR) in 2015 (as a long term solution). The MSR adjusts auction volumes according to predefined thresholds of the total number of allowances in circulation (TNAC) so as to maintain the carbon market in balance.

In July 2021, the European Commission adopted a package of proposals (“Fit for 55”) to deliver the European Green Deal, which provides an action plan, to boost the efficient use of resources by moving to a clean, circular economy and to restore biodiversity and cut pollution. The proposals aim to make the EU's climate, energy, land use, transport and taxation policies fit for the task of reducing net GHG emissions by at least 55% by 2030 compared to 1990 levels. It establishes for the EU ETS a new emissions reduction target of 61% below 2005 levels by 2030 (compared to 43% below 2005 levels currently), a lower overall emissions cap, and a steeper annual emissions reduction of 4.2% instead of the current 2.2% per year.

Chapter 3: Model for the EU ETS and the MSR

3.1 – Model framework for the EU ETS

The EU ETS is a competitive emissions trading system with full banking and limited borrowing of emission permits over time, firms can bank allowances from one period to the next or tap into free allocations distributed in the first quarter in a given year to meet liabilities for the previous year. It is a dynamic model as the number of banked allowances from a given year affects the total supply of allowances in the subsequent year. Quemin and Trotignon (2019) demonstrate that firms in the EU ETS use a rolling finite horizon approach in their planning decisions in order to hedge regulatory uncertainty. Firms try to reduce uncertainty making the most immediate decisions by optimizing over a finite number of periods ahead for which they can make reasonably good forecasts about the relevant exogenous factors entering into their decision making. Only the first-period optimal decisions are implemented and the procedure is sliding, meaning it repeats every period thereafter, each time over the rolling horizon. Agents can also revise or update their forecasts as they initiate each new planning cycle.

Quemin and Trotignon (2019) develop a discrete time model indexed by $t \geq 1$ for the EU ETS. The system starts at date 1 and firms' compliance is required at each date t . The regulator (the European Commission) sets a cap on system-wide emissions for each date t , which consists of freely allocated and auctioned permits, respectively f_t and a_t . Some fixed quantity of offset credits O may also be surrendered for compliance over a given time period and o_t denotes the volume of offsets used at date t with $\sum_t o_t \leq O$. The offset credits could be used during Phase 2 directly for compliance, in Phase 3 they had to be exchanged for EUA, while from Phase 4 international credits can no longer be used for compliance (i.e. $O = 0$ from 2021). At each date t , it's assumed that regulated firms fully acquit their compliance obligations and remit as many permits and offsets as needed to cover their current emissions. The decentralized market equilibrium can be characterized indirectly as the solution to joint compliance cost minimization among all firms (Montgomery, 1972; Rubin, 1996). The model uses a representative firm approach which is well-documented and widely employed in the literature (e.g. Fell et al., 2012; Kollenberg & Taschini, 2019).

For each firm, e_t and u_t denote its levels of realized and baseline (unregulated) emissions at date t , respectively. Firms must abate the difference $u_t - e_t \geq 0$ which determines the minimum total abatement cost function at date t , represented by C_t with $C'_t, C''_t > 0$, meaning abatement cost curves are increasing convex functions. The firm's baseline emissions u_t depend on business cycle fluctuations (Koch et al., 2014; Bel & Joseph, 2015) and the variable performances of

complementary climate and energy policies flanking the permit market that can affect counterfactual emission levels independently of the permit price (Borenstein et al., 2016; Burtraw & Keyes, 2018). Baseline emissions represent the emissions in a given year that would be emitted in the absence of carbon price incentives.

On the supply side of allowances, there exist small annual discrepancies between announced and realized cap levels, the future cap trajectories $\{f_t\}_t$ and $\{a_t\}_t$ can be affected by regulatory changes, and $\{o_t\}_t$ depends on external offset market conditions (de Perthuis & Trotignon, 2014; Ellerman et al., 2016). To signify that future permit demand and supply conditions are uncertain in nature for the firm, the tilde notation is used.

3.1.1 – Competitive intertemporal equilibrium

The firm chooses emissions and abatement by optimizing intertemporal abatement costs. The firm's annual demand for permits has two components, one for annual compliance and the other for intertemporal arbitrage. That is, at any date t , given the prevailing permit price p_t and realized baseline u_t , the firm's emission level, or demand for permits for compliance $e_t^*(p_t, u_t)$, satisfies the first-order necessary condition

$$C'_t(u_t - e_t^*(p_t, u_t)) - p_t = 0 \quad (1)$$

In addition, the firm can over-comply relative to total contemporaneous available supply and bank unremitted permits into future dates or it can under-comply and borrow yet-unallocated permits from its future self and use them to achieve full compliance today. While banking is unlimited, borrowing at date t is authorized up to a limit $l_t \geq 0$. Borrowing is possible in the EU ETS because freely allocated year- t vintage permits are issued two or four months prior to the year- $(t - 1)$ compliance deadline. Therefore $l_t = f_{t+1}$ as firms can effectively tap into their allotment for two consecutive years. As the firm cost minimizes over time, limited intertemporal trading opportunities imply a no-arbitrage condition. Permit banking, whose level at date t is denoted b_t , constitutes the second determinant of permit demand and satisfies the following two conditions with complementary slackness

$$b_t + l_t \geq 0 \quad \perp \quad p_t - \beta \mathbb{E}_t\{p_{t+1}\} \geq 0 \quad (2)$$

where $\mathbb{E}_t\{\cdot\}$ denotes expectation conditional on all information available to the firm at date t and $\beta = (1 + r)^{-1}$ is the firm's discount factor with r the discount rate, possibly inclusive of a permit-

specific risk premium.¹³ As long as $\beta \mathbb{E}_t\{p_{t+1}\} > p_t$, banking is profitable and increases date t permit demand, which raises p_t and lowers $\mathbb{E}_t\{p_{t+1}\}$ until all arbitrage opportunities are exhausted and the firm breaks even so the cost-of-carry price coincides with the spot price grown at the discount rate, i.e. $\beta \mathbb{E}_t\{p_{t+1}\} = p_t$. Conversely, as long as $\beta \mathbb{E}_t\{p_{t+1}\} < p_t$, borrowing is profitable but only authorized up to l_t (or f_{t+1}). As soon as this constraint is binding, the connection between current and expected future prices ceases to hold and the price rises at a rate less than the discount rate. In sum, the price can rise at a rate at most as high as the discount rate in a rational expectations equilibrium. Banked permits add to future permit supply (while borrowed permits subtract from it), meaning total available supply at date t amounts to $f_t + a_t + o_t + b_{t-1}$. Market clearing at date t , which implies that total supply equalizes total demand, is therefore

$$f_t + a_t + o_t + b_{t-1} = e_t + b_t \quad (3)$$

Combining the compliance, no-arbitrage, and market-clearing conditions (1), (2) and (3) leads to two regimes in the equilibrium price and emission dynamics

$$p_t = \max \{ \beta \mathbb{E}_t\{p_{t+1}\}; C'_t(u_t - (l_t + f_t + a_t + o_t + b_{t-1})) \} \quad (4a)$$

$$e_t = \min \{ e_t^*(\beta \mathbb{E}_t\{p_{t+1}\}, u_t); l_t + f_t + a_t + o_t + b_{t-1} \} \quad (4b)$$

$$\text{with } b_t = f_t + a_t + o_t + b_{t-1} - e_t \geq -l_t \quad (4c)$$

The first regime features intertemporal flexibility in the firm's emission stream in line with Hotelling's rule in expectation with $b_t > -l_t$ ¹⁴. In the second regime the borrowing constraint is binding ($b_t = -l_t$) so that permit demand becomes solely determined by annual compliance requirements in (1) and emissions are pegged to the contemporaneous amount of permits on hand. Limited borrowing implies an asymmetric demand shock dampening potential for the market and induces a non-linearity so that no closed-form solution to (4) can be derived. In principle, the firm can entirely smooth out the price impact of a downward demand shock (temporary glut) by stockpiling more permits while it can only do so for a symmetric upward shock (temporary shortage) to the extent that the bank is not too small.

¹³ Schennach (2000), Perino & Willner (2016) and Kollenberg & Taschini (2019) introduce an exogenous risk premium on top of the risk-free rate to capture the impacts of future emissions uncertainty on the firm's decisions, in the spirit of the Capital Asset Pricing Model.

¹⁴ This regime is always finite in time but may not be unique under uncertainty. (e.g. Schennach (2000)).

3.1.2 – Equilibrium with rolling horizons

The representative firm in the model minimizes its abatement cost with rolling horizons and limited foresight. In the model, the firm optimizes the level of emissions in each year within a time horizon, considering its forecast of baseline emissions and supply of allowances. The supply of allowances is determined by the EU ETS cap and augmented by MSR dynamics. The difference between the baseline emissions and the supply of allowances over this time horizon determines the total abatement required from the firm, thus entering its optimization problem as a budget constraint. The firm minimizes the net present value of abatement costs over this time horizon given this budget constraint. The forecast of baseline emissions may deviate from the actual baseline emissions due to an assumption on limited foresight. Shocks to the system will affect the firm's expectations and therefore its optimal choice of emissions and abatement.

At the beginning of any date t , u_t, f_t, a_t and o_t are given and known to the firm, which also keeps track of the bank b_{t-1} (with $b_0 = 0$)¹⁵. Optimizing over a finite horizon $h \geq 0$ within which the firm is confident about its forecasts of future exogenous variables, the firm selects its date- t emission e_t and implied bank b_t by solving the following program

$$\min_{\{e_\tau\}_{\tau=t}^{t+h}} \sum_{\tau=t}^{t+h} \beta^{\tau-t} C_\tau(\hat{u}_\tau^t - e_\tau) \quad (5a)$$

$$\text{subject to } 0 \leq e_\tau \leq \hat{u}_\tau^t, \quad b_\tau = b_{\tau-1} + \hat{f}_\tau^t + \hat{a}_\tau^t + \hat{o}_\tau^t - e_\tau \geq -\hat{f}_{\tau+1}^t \quad (5b)$$

$$\text{and } \sum_{\tau=t}^{t+h} [\hat{u}_\tau^t - e_\tau] \geq \sum_{\tau=t}^{t+h} [\hat{u}_\tau^t - (\hat{f}_\tau^t + \hat{a}_\tau^t + \hat{o}_\tau^t)] - b_{t-1}, \quad (5c)$$

where \hat{x}_τ^t denotes the date- t forecast for $x = \{u, f, a, o\}$ at date $\tau \geq t$. The objective function (5a) specifies that the firm seeks to minimize the net present value of its abatement costs over the time horizon from year τ to year $\tau + h$. (5b) reiterates that the firm must choose an emissions level that is less than or equal to its baseline emissions and that the number of banked allowances in a given year correspond to the number of unused allowances from the annual supply facing the firm. (5c) specifies the firm's date- t assessment of the system stringency over the horizon h , that is the sum of forecasted yearly raw abatement efforts $\hat{u}_\tau^t - (\hat{f}_\tau^t + \hat{a}_\tau^t + \hat{o}_\tau^t)$ corrected for the initial bank b_{t-1} . Then, (5a) dictates that this forecasted overall abatement effort be spread over the horizon in accordance with the equimarginal value principle.

¹⁵ Offset usage is assumed exogenous to the firm problem

Under a rolling horizon, the firm solves for the equilibrium path from date t up to $t + h$ given its current forecasts $\{\hat{x}_\tau^t\}_\tau$, but only implements the first date of the plan, which pins down the state variable for the next date. At date $t + 1$ the firm revises its forecasts based on new information about x and initiates a new planning cycle from date $t + 1$ to $t + h + 1$ taking the state variable b_t as given. This date-on-date solving and updating of finite plans and the sequential execution of the first date of these plans then unfolds over time. Technically, a rolling horizon shrinks the firm's problem dimensionality from uncertainty to certainty given appropriate forecasts.

3.2 – Model for the MSR

In the EU ETS firms are allowed to bank EUA from one period to the next without restrictions, meaning that allowances prices are linked over time and should rise at the discount rate due to intertemporal arbitrage, as shown in paragraph 3.1. In practice prices remained very low (between 3-9 €/t) due to the economic downturn and a structural supply/demand imbalance in the first phases of the system. The MSR was introduced to tackle these imbalances, its purpose is to avoid that the EU carbon market operates with a large structural surplus of allowances, with the associated risk that this prevents the EU ETS from delivering the necessary investment signal to achieve the EU's emission reduction target in a cost-efficient manner. The MSR was introduced in 2015, amended in 2018 and became operational in 2019. It is designed to automatically adjust the quantity of allowances auctioned when demand is lower than anticipated, due to policy changes, economic drivers, changes in relative energy prices, or changes to market participants abatement or other behavior. The MSR affects the overall cap by reducing the total number of allowances in circulation and ultimately cancelling allowances based on a complex mechanism (cancellation mechanism) which permanently invalidates excess allowances in MSR holding account above prior year auction volume (from 2023 onward).

The Market Stability Reserve is a supply side control imposed by the regulator. This mechanism adjusts contemporaneous supply based on the value of a given market indicator (the TNAC) relative to some predefined thresholds. The MSR is a reserve of set-aside permits whose stock at date t is denoted by $s_t \geq 0$. The MSR can be modeled as a banking corridor which automatically adjusts current auctions a_t based on banking history $\{b_\tau\}_{\tau < t}$ according to

$$a_t \leftarrow a_t - \min \{a_t; R \cdot \sum_{\tau < t} \mathbb{1}\{b_\tau > \bar{b}\} x_\tau b_\tau\} + \min \{I; s_{t-1}\} \cdot \sum_{\tau < t} \mathbb{1}\{b_\tau > \underline{b}\} x_\tau \quad (6)$$

where $\mathbb{1}\{\cdot\}$ is the indicator function which is equal to 1 when the event is realized and equal to 0 otherwise, $\underline{b} > 0$ and $\bar{b} > \underline{b}$ are the lower and upper bank thresholds, $I > 0$ is an injection quantity, $R \in [0; 1]$ is an absorption rate and $\{x_\tau\}_{\tau < t}$ are historical weights such that $x_\tau \in [0; 1]$ for all $\tau < t$ and $\sum_{\tau < t} x_\tau = 1$. In parallel, the stock of permits stored in the reserve follows the complementary dynamics

$$s_t = s_{t-1} + \min \{a_t; R \cdot \sum_{\tau < t} \mathbb{1}\{b_\tau > \bar{b}\} x_\tau b_\tau\} - \min \{I; s_{t-1}\} \cdot \sum_{\tau < t} \mathbb{1}\{b_\tau > \underline{b}\} x_\tau \quad (7)$$

In words, when $b_{\tau < t}$ is above \bar{b} , a predefined share $x_\tau R$ thereof is withheld from auctions at date t and placed in the reserve. Symmetrically, when $b_{\tau < t}$ is below \underline{b} and the current stock of the reserve allows, a fixed quantity of reserve permits $x_\tau I$ is added to auctions at date t . Otherwise, the banking corridor is inactive. Because the shift in auctions is determined by the banking history it is fixed once and for all at the beginning of each date.

The Market Stability Reserve functions by triggering adjustments to the annual auction volumes when the total number of allowances in circulation is outside of a predefined range. If TNAC exceeds the threshold of 833 million allowances, permits are added to the Reserve (24% of TNAC); while 200 million of allowances are released from the Reserve if TNAC is lower than 400 million. From 2024 the intake rate will reduce to 12% of the previous year's TNAC, and the release rate will be reduced to 100 million allowances. In practical terms, allowances are added to the Reserve by auctioning less, and released from the Reserve by auctioning more allowances in the future. Given this data the parameters for the MSR model are $\bar{b} = 833$ million allowances, $\underline{b} = 400$ million allowances, $R = 0.24$ and $I = 200$ million allowances until 2023 ($R = 0.12$ and $I = 100$ million allowances from 2024). The Market Stability Reserve adjustment to auctions in period t is a function of the TNAC in period $t - 1$ and $t - 2$. The TNAC in year $t - 1$ adjusts the auction from September in year t to August in year $t + 1$. This means that a third of the effect of TNAC in period $t - 1$ will be adjusted in period t and two thirds in period $t + 1$, hence the historical rates are $x_{t-2} = \frac{2}{3}$ and $x_{t-1} = \frac{1}{3}$ to account for the mismatch between the MSR and compliance calendars.

The banking corridor as defined above, can in principle be expected to preserve the cumulative emissions cap as it essentially rearranges the auction schedule. Indeed, after a certain period the bank will pass below \underline{b} implying that the reserve should eventually empty. This ceases to be the case, however, if the corridor is equipped with an add-on cancellation mechanism that retires and

invalidates permits stored in the reserve in excess of a certain threshold. In this case, the reserve stock is further adjusted such that

$$s_t \leftarrow s_t - \max \{0; s_t - k_t\} \quad (8)$$

where $k_t \geq 0$ is the maximum number of permits that can be stored in the reserve at date t . The cumulative emissions cap is endogenized and becomes a market outcome. Whether and by how much it is reduced depends on the thresholds $\{k_t\}_t$ and the equilibrium dynamics of the reserve stock, which itself hinges on the initial bank and reserve stock conditions and is ultimately governed by the firm's horizon, discount rate and responsiveness to the control. For The MSR the cancellation mechanisms will be implemented from 2023 and will operate such that any permits stored in a given year in excess of the number of auctioned permits in the previous year are invalidated (European Parliament & Council, 2018). Hence $k_t = a_{t-1}$ which is endogenously determined via the MSR, following equation (6).

3.3 – Observations and results

The firm takes the MSR into account when making its intertemporal optimization. The solution is estimated by finding a fixed point of the firm's optimization and the forecasted response by the MSR. To find this fixed point the firm repeatedly updates its optimal plan for emissions and abatement given how its course of actions will affect future MSR response and allowance supply. This is repeated until convergence is obtained.

As described earlier in paragraph 3.1, the main drivers of emissions, prices and TNAC pathways are the baseline emissions, cap trajectory, interest rate and the length of the anticipation period. Changes in policy parameters will affect the perceived scarcity of emissions allowances and therefore the firms' behavior on emissions and abatement.

The cumulative difference between the cap and the baseline emissions over the anticipation period determines the necessary abatement over time. A tightening of the cap or the increase in baseline emissions will both increase the level of abatement required from the firm, which would spread the burden by abating more every year.

A higher interest rate implies greater discounting for future costs, making the firm shift its costly abatement from today into the future, aiming to reduce the net present value of cumulative abatement costs.

A longer length of anticipation will make the firm account for the abatement required over a long-time horizon. Because the cap declines faster than the baseline emissions, looking further into the future means anticipating a stronger need for abatement, thereby reducing emissions and increasing abatement today. Another consequence of a longer anticipation length is that it tends to attenuate the impact from unanticipated shocks.

The MSR affects the optimization problem first by changing the supply of allowances and second by affecting the firm's anticipation of future supply. After the MSR releases or takes in allowances it changes the cap and thus changes the total amount of abatement necessary over the anticipation period. A larger MSR intake would tighten supply and require the firm to abate more, reducing its planned emissions. But the firm also forecasts the effect of the MSR on auctions because of the choices it plans to make for the years $t + 1$ to $t + h$. The firm's optimal decision will therefore involve planning ahead on how its action will affect MSR intakes or releases.

Increasing the auction share under the cap tends to increase the TNAC. As the firm can meet its emissions obligations for a given year by using free allowances allocated in the first quarter in the next year, a higher auction share would reduce the number of free allowances that the firm can use to meet its compliance obligations. In other words, this represents a tighter borrowing constraint in the model.

The introduction of the MSR and the increase in LRF (linear reduction factor) from 1.74% to 2.2% for phase 4 were able to increase the price level for allowances. The price surged and stabilized at the range of 20-30 €/t from 2019 to 2020. Since autumn 2020 the prices increased even more reaching a price range of 50-60 €/t in 2021 and a range of 80-90€/t in mid-2022.

From 2019 the MSR has begun to address historical imbalances in the EU ETS market. This includes an adjustment of 397 million allowances withdrawn from auction volumes over 2019, 308 million allowances withdrawn from auction volumes over 2020-21, and 379 million allowances withdrawn from auction volumes over the period 2021-22, representing 24% of the previous year's published TNAC in each case, after accounting for Brexit. The MSR's first intakes occurred over January to August 2019 and September to January 2019, while the second tranche of intake occur from September 2020 to August 2021. These intakes were triggered by the TNAC levels in 2017 and 2018, which were both in the range of 1.65 billion allowances, well in excess of the upper threshold of 833 million allowances. In total, 397 million allowances were withdrawn from auction volumes from 1 January 2019 to 31 December 2019. Likewise, the 2019 TNAC triggered an MSR intake of 308 million allowances to be carried out from 1 September 2020 to 31 August 2021. These

adjustments alongside others such as backloading reduced the 2019 TNAC to 29% below its high in 2013.

In the next paragraph the MSR adjustment for the auction volumes for the period 2022-23 is determined following the calculation of the 2021 TNAC.

3.4 – Total Number of Allowances in circulation (TNAC)

By May 15 of each year, from 2017, the Commission has to publish the total number of allowances in circulation¹⁶ in order to determine whether some of the allowances intended to be auctioned should be placed into the Reserve or released from it, following the parameters in the model in paragraph 3.2.

The number of allowances available to market participants in a given year is a function of the allowances created under the EU ETS cap and allowances banked from previous years compared to cumulative emissions and cancellations. It is calculated on an annual basis with the inclusion of data from the previous calendar year. The level of the TNAC determines MSR adjustments to auction volumes and is found with the following formula:

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

There are three different elements that determine the total number of allowances in circulation: first, the supply of allowances since 1 January 2008; second, the demand for allowances (number of allowances surrendered and cancelled); and third, the holdings of the Reserve.

The supply of allowances to the market is determined by a number of different elements:

- allowances banked from the period 2008-12 (Phase 2) of the EU ETS (the European Commission (2022) estimates a number of 1.749.540.826 allowances)¹⁷,
- allowances allocated for free between 1 January 2013 and 31 December 2021, including the allowances allocated from the New Entrants Reserve (NER), which is a set aside of EU allowances reserved for new operators or existing operators who have significantly increased capacity (7.141.195.439),
- allowances not allocated to installations that were placed in the Market Stability Reserve in 2020 (886.806.455). 50 million unallocated allowances auctioned for the Innovation Fund

¹⁶ It does not include aviation allowances and verified aviation emissions since the Market Stability Reserve relates to allowances for stationary installations, pursuant to article 10(1) of Directive 2003/87/EC

¹⁷ Source: Communication from the Commission Publication of the total number of allowances in circulation in 2021 for the purposes of the Market Stability Reserve under the EU Emissions Trading System established by Directive 2003/87/EC and of the number of unallocated allowances during the period 2013-2020 (OJ C/195, 13.05.2022, p. 2-7)

must be deducted from these volumes ($886.806.455 - 50.000.000 = 836.806.455$),

At the beginning of 2021, 200 million allowances were transferred from the Market Stability Reserve to the NER for the period 2021-2030 ($836.806.455 - 200.000.000 = 636.806.455$)

- allowances issued for auctioning between 1 January 2013 and 31 December 2021, including early auctions (6.598.419.287),
- allowances deducted from auctioning volumes during the period 2014-2016 (900.000.000), and allowances deducted from auctioning volumes from 2019 to 2021 (1.095.875.607)
- allowances monetized by the European Investment Bank for the purposes of the 'NER300' program (300.000.000),
- international credit entitlements exercised by installations in respect of emissions up to 31 December 2020 (497.248.017). International credit entitlements can no longer be used as of the period 2021-2030.

Summing up, total supply estimated in 2022 by the European Commission is equal to 18.919.085.631 allowances.

The demand consists of:

- the total verified emissions from installations between 1 January 2013 and 31 December 2021 (14.836.567.505 tons),
- allowances cancelled in that same period (621.882 allowances).

For a total demand of 14.837.189.387 allowances.

The holdings of the Market Stability Reserve in 2022 are the sum of:

- 900 million allowances deducted from auctioning volumes during the period 2014-2016 and placed in the Reserve when it began operating on 1 January 2019.
- 772.749.992 allowances placed in the Reserve in the period from 1 January 2019 to 31 December 2020.
- 196.823.820 allowances placed in the Reserve in the period from 1 January 2021 to 31 August 2021
- 126.301.795 allowances placed in the Reserve in the period from 1 September 2021 to 31 December 2021.
- 886.806.455 unallocated allowances added to the Market Stability Reserve at the end of 2020.

- Minus 50 million allowances that were taken out of the MSR and auctioned in 2020 for the Innovation Fund.
- Minus 200 million allowances that were taken out of the MSR and placed in the NER at the beginning of 2021.

Reaching a total of 2.632.682.062 allowances.

Hence the Total Number of Allowances in Circulation in 2021 is equal to 1.449.214.182 allowances ($18.919.085.631 - 14.837.189.387 - 2.632.682.062 = 1.449.214.182$). Therefore, since it is higher than the 833 million allowances threshold, in line with Decision (EU) 2015/1814, a total of 347.811.404 allowances will be placed in the Market Stability Reserve (24% of 1.449.214.182) over a 12-month period from 1 September 2022 to 31 August 2023.

Conclusions

In conclusion, The EU ETS has proven to be a very effective policy for pollution reduction, lowering emissions by around 43% since its implementation and contributing significantly, together with other policies, to the achievement of a 31% reduction of GHG emissions below 1990 levels in 2020, surpassing the target of 20%. Even though it had many issues following its first two phases such as the oversupply of allowances given an overestimation of emissions, the EU ETS has been promptly modified and revised multiple times in order to overcome its problems and achieve more efficiently the increasingly ambitious pollution reduction targets. The implementation of the MSR as a supply control mechanism, has been successful in decreasing the total amount of allowances in circulation tackling the problem of supply/demand imbalances and increasing the allowance price. Moreover, the MSR has increased the flexibility of the EU ETS to respond to unexpected shocks in the allowance market by responding promptly to changes in the TNAC, increasing or decreasing the number of auctioned allowances. Since its implementation the MSR has withheld from the market and placed in the reserve approximately 1.4 billion allowances and has contributed to increasing the price to a level of 80-90€/t in 2022. The forthcoming changes in the EU ETS will be the implementation of the cancellation mechanism in 2023 that will invalidate all allowances in the reserve that are in excess of the number of auctioned allowances, and the change in the MSR parameters in 2024; namely the retention rate R will decrease from 0.24 to 0.12 and the injection quantity I will be lowered from 200 million to 100 million allowances. As a consequence, these alterations will decrease the number (cancellation mechanism) and the flow (parameters changes) of allowances in the reserve.

References

- Bel, G. & Joseph, S. (2015). *Emission Abatement: Untangling the Impacts of the EU ETS and the Economic Crisis*. *Energy Economics*, **49**, 531–9.
- Borenstein, S., Bushnell, J., Wolak, F. A. & Zaragoza-Watkins, M. (2016). *Expecting the Unexpected: Emissions Uncertainty and Environmental Market Design*. Working Paper 20999, NBER.
- Burtraw, D. & Keyes, A. (2018). *Recognizing Gravity as a Strong Force in Atmosphere Emissions Markets*. *Agricultural & Resource Economics Review*, **47**(2), 201–19.
- Eionet Report - ETC/ATNI 2020/4, *Costs of air pollution from European industrial facilities 2008–2017*, 2021
- Ellerman, A. D., Marcantonini, C. & Zaklan, A. (2016). *The European Union Emissions Trading System: Ten Years and Counting*. *Review of Environmental Economics & Policy*, **10**(1), 89–107.
- EU Emissions Trading System, European Commission, https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets_it
- European Commission (2015), *EU ETS Handbook*, European Union
- European Commission (2021), *Communication from the Commission Publication of the total number of allowances in circulation in 2020 for the purposes of the Market Stability Reserve under the EU Emissions Trading System established by Directive*, official journal of the European Union
- European Commission (2021), *Directorate-General for Climate Action, Review of the EU ETS market stability reserve: final report*, Publications Office of the European Union
- European Commission (2021), *Report from the commission to the European parliament and the council on the Functioning of the European Carbon Market in 2020 pursuant to Articles 10(5) and 21(2) of Directive 2003/87/EC (as amended by Directive 2009/29/EC and Directive (EU) 2018/410)*
- European Commission (2022), *Communication from the Commission Publication of the total number of allowances in circulation in 2021 for the purposes of the Market Stability Reserve under the EU Emissions Trading System established by Directive 2003/87/EC and of the number of unallocated allowances during the period 2013-2020*, official journal of the European Union

- European Environmental Agency (2014), *Costs of air pollution from European industrial facilities 2008–2012 — an updated assessment*
- European Parliament & Council (2018). *Directive (EU) 2018/410*. OJ L.
- Externalities of air pollution, <https://transportgeography.org/contents/chapter4/transportation-and-environment/air-pollution-externalities/>
- Fell, H., Burtraw, D., Morgenstern, R. D. & Palmer, K. L. (2012). *Soft and Hard Price Collars in a Cap-and-Trade System: A Comparative Analysis*. *Journal of Environmental Economics & Management*, **64**(2), 183–98.
- Koch, N., Fuss, S., Grosjean, G. & Edenhofer, O. (2014). *Causes of the EUETS Price Drop: Recession, CDM, Renewable Policies or a Bit of Everything?—New Evidence*. *Energy Policy*, **73**, 676–85.
- Kollenberg, S. & Taschini, L. (2019). *Dynamic Supply Adjustment and Banking under Uncertainty in an Emissions Trading Scheme: The Market Stability Reserve*. *European Economic Review*, **118**, 213–26.
- Kollenberg, S. & Taschini, L. (2019). *Dynamic Supply Adjustment and Banking under Uncertainty in an Emissions Trading Scheme: The Market Stability Reserve*. *European Economic Review*, **118**, 213–26.
- LIFE ETX (2021) *EU ETS 101 – A beginner’s guide to the EU’s Emissions Trading System*
- Montgomery, W. D. (1972). *Markets in Licenses and Efficient Pollution Control Programs*. *Journal of Economic Theory*, **5**(3), 395–418.
- Perino, G. & Willner, M. (2016). *Procrastinating Reform: The Impact of the Market Stability Reserve on the EU ETS*. *Journal of Environmental Economics & Management*, **80**, 37–52.
- de Perthuis, C. & Trotignon, R. (2014). *Governance of CO2 Markets: Lessons from the EU ETS*. *Energy Policy*, **75**, 100–6.
- Quemin S., Trotignon R. (2019), *Emissions Trading with Rolling Horizons*, Centre for climate change economics and policy
- Rosen H. S., Gayer T. (2014), *Public Finance*, Mc Graw Hill Education

Rubin, J. D. (1996). *A Model of Intertemporal Emission Trading, Banking and Borrowing*. Journal of Environmental Economics & Management, **31**(3), 269–86.

S. Osorio, O. Tietjen, M. Pahle, R. C. Pietzcker, O. Edenhofer (2021), *Reviewing the Market Stability Reserve in light of more ambitious EU ETS emission targets*, Elsevier

Schennach, S. M. (2000). *The Economics of Pollution Permit Banking in the Context of Title IV of the 1990 Clean Air Act Amendments*. Journal of Environmental Economics & Management, **40**(3), 189–210.

The economics of pollution, <https://www.khanacademy.org/economics-finance-domain/microeconomics/market-failure-and-the-role-of-government/environmental-regulation/a/the-economics-of-pollution-cn/x>