

SUSTAINABLE FINANCE: CARBON MARKETS

ENVIRONMENTAL FINANCE AND INVESTMENTS

Companion Book — A conceptual synthesis of the volume by M. Chesney, J. Gheyssens, A. C. Pana and L. Taschini (2nd ed., Springer, 2016), updated to the regulatory, institutional and market framework in force in 2026

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Thematic report — Carbon markets and EUAs as an asset class

Document intended exclusively for professional and institutional investors

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Methodological note

This companion book revisits and updates the content of the volume “Environmental Finance and Investments” (2nd edition, Chesney, Gheysens, Pana, Taschini, Springer 2016 – hereinafter “the volume/the work/the original version/the original edition”), focusing on the underlying economic and financial concepts and avoiding formal mathematical notation as far as possible. Where the original text presents a model, a theorem or a formula, this book explains the economic intuition behind it, its operational meaning and its practical implications, often accompanied by an explanatory chart built specifically to illustrate the relationship described (the charts included here are original elaborations for explanatory purposes).

Then comes the most important part: the update. Compared with the original version, the institutional, regulatory and market framework has been fully revised to reflect developments between 2016 and 2026: the entry into force of the Paris Agreement, the IPCC Sixth Assessment Report, the completion of the Agreement’s governance architecture (NDCs, Global Stocktake, Article 6), the evolution of the EU ETS through the European Green Deal, the Fit for 55 package, ETS2 and the Carbon Border Adjustment Mechanism (CBAM), and the transformation of European Union Allowances (EUAs) into a fully-fledged financial asset class. References that are now outdated (in particular the central role once attributed to the Kyoto Protocol) have been updated, while the timeless theoretical framework of the original volume — the analysis of externalities, the comparison between taxes and permits, the real options approach to investment decisions — has been retained in full, as it is unaffected by the passage of time.

The work unfolds over **eight chapters**: to the seven chapters of the original version, a chapter has been added that is devoted specifically to the infrastructure and financial instruments of the European emission allowance market, made necessary by the growth and sophistication this market has achieved over the past decade. The concluding chapter of the original work, devoted to emission price dynamics, has been expanded into a much more in-depth treatment of the European Union Allowance (EUA) market as an asset class, which today represents one of the most significant areas where environmental finance meets traditional financial markets.

1. Introduction

Climate change is today one of the main forces transforming the world economy. When the original work was published (2016), the debate still focused mainly on the effectiveness of mitigation policies and the design of emission markets; by 2026 the context has changed profoundly. The climate challenge is no longer only about reducing greenhouse gas emissions: it directly affects industrial competitiveness, energy security, international trade policy, financial risk management and capital allocation.

The entry into force of the **Paris Agreement** in 2016 radically changed the architecture of global climate governance. Unlike the Kyoto Protocol, which was based on binding targets limited to industrialised countries, the new system involves virtually all economies through *Nationally Determined Contributions* (NDCs), updated periodically with the aim of holding the increase in global average temperature well below 2°C above pre-industrial levels and pursuing efforts to limit it to 1.5°C.

At the same time, the European Union has taken a leading role in implementing climate policy. With the **European Green Deal**, the **Fit for 55** legislative package, the **REPowerEU** plan, the **Net Zero Industry Act**, the **Critical Raw Materials Act** and the revision of the **EU ETS**, European climate policy has become one of the main instruments of industrial policy and economic competitiveness. Climate neutrality by 2050 is now a legally binding objective for the European Union and provides the framework within which corporate investment strategies are set.

Finance, too, has undergone a profound transformation. Sustainability has gradually shifted from a voluntary criterion of social responsibility to a structural factor in risk assessment and capital allocation. Regulations such as the **Sustainable Finance Disclosure Regulation (SFDR)**, the **EU Taxonomy** and the **Corporate Sustainability Reporting Directive (CSRD)** have introduced new disclosure requirements, changing the way investors, banks and companies assess climate risk and the opportunities arising from the energy transition.

In this context, the carbon market has acquired unprecedented importance. While in the first phase of the EU ETS emission allowances were regarded mainly as an administrative tool for regulatory compliance, today **European Union Allowances (EUAs)** form one of the most liquid and sophisticated environmental markets in the world, traded through spot, futures and options contracts and used as a key reference by utilities, energy-intensive companies, financial intermediaries and institutional investors. The price of CO₂ has become an economic signal that directly influences investment decisions, the competitiveness of different energy technologies and the appraisal of numerous industrial projects.

At the same time, there has been a strong expansion of **voluntary carbon markets** (*Voluntary Carbon Markets*, VCM), in which companies and investors buy carbon credits to voluntarily offset part of their residual emissions. Although their characteristics differ profoundly from those of regulated systems such as the EU ETS, their growth bears witness to the progressive recognition of carbon as a new environmental and financial asset class.

Yet the fundamental question that forms the common thread of the original work remains unchanged: **under what conditions can carbon pricing instruments¹ drive efficient investment and emission-reduction decisions?** This question, which in 2016 concerned mainly the design of cap-and-trade systems, now extends to the appraisal of energy transition investments, climate risk management and the interaction between public policy, financial markets and technological innovation.

¹ By carbon pricing instruments we mean, without distinction, carbon taxes and subsidies, pollution permits (e.g. EUAs, see Chapter 8) and carbon credits (see section 3.5).

The volume therefore retains the two-part structure of the original edition. The first part (chapters 2-5) addresses the problem at the macroeconomic and institutional level: climate science, international governance and the evolution of carbon markets, environmental policy instruments and the relationship between economic growth and the environment. The second part, more technical and significantly expanded in this edition (chapters 6-8), adopts the perspective of the regulated firm and the investor, developing the real options approach to investment decisions, the infrastructure and financial instruments of the European emission allowance market, and an in-depth analysis of European Union Allowances as a financial asset class.

A common thread runs through the entire book: investment decisions in technology (or in permits) under an environmental regulatory regime share the typical features of every real investment decision — they are partially or totally irreversible, they can be postponed, and they are taken under uncertainty. The real options framework, borrowed from financial option pricing theory, remains the most suitable tool for capturing this decision-making flexibility, as an alternative to the traditional Net Present Value (NPV) criterion, widely used in the appraisal of private equity projects.

2. The climate change problem

2.1. The relationship between greenhouse gas concentration and global temperature

Climate change is today one of the best-documented physical phenomena in the scientific literature. Instrumental observations, palaeoclimate reconstructions and climate models converge in attributing almost all of the warming observed since the mid-20th century to the increase in atmospheric concentrations of greenhouse gases generated by human activities (see box). The IPCC (see Chapter 3), in its **Sixth Assessment Report (AR6)**, concludes with unprecedented confidence that human influence has warmed the atmosphere, the oceans and the land.

In Focus: The main greenhouse gases

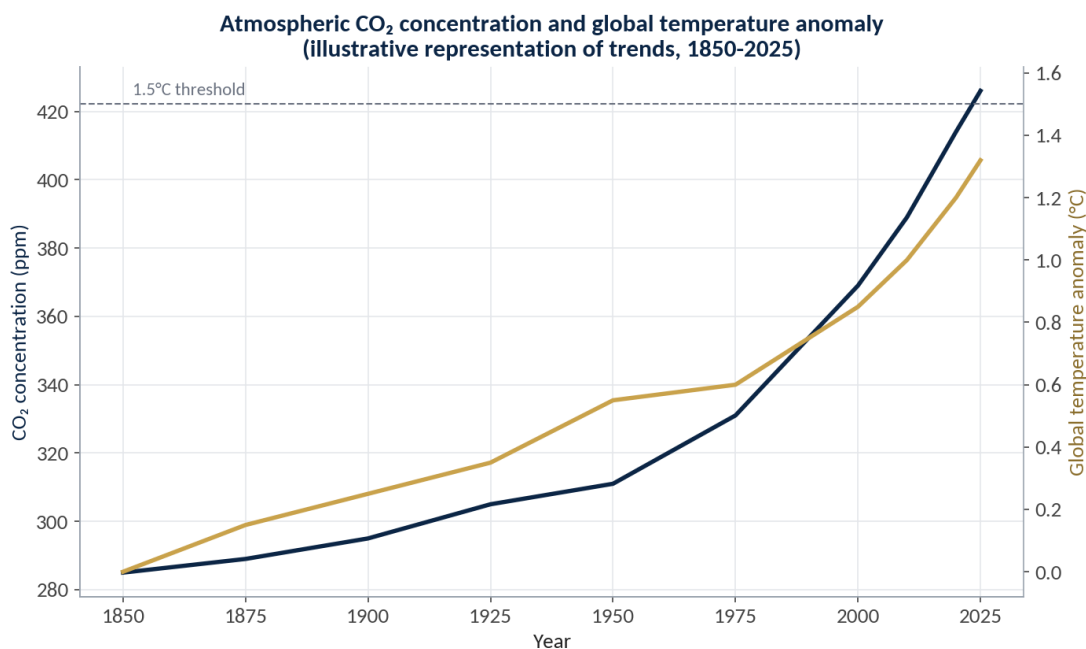
The main greenhouse gases (GHGs) recognised internationally — and also covered by the Kyoto Protocol — are six:

1. **Carbon dioxide (CO₂)** — the most important in terms of total volume, originating mainly from the combustion of fossil fuels (coal, oil, gas) and from deforestation.
2. **Methane (CH₄)** — produced by agriculture (livestock, rice paddies), landfills and fossil fuel extraction. It has a much higher global warming potential (GWP) than CO₂ in the short term, but degrades more quickly in the atmosphere.
3. **Nitrous oxide (N₂O)** — derives mainly from agricultural fertilisers and some industrial processes; it persists in the atmosphere for more than a century.
4. **Hydrofluorocarbons (HFCs)** — synthetic gases used as refrigerants and in air-conditioning systems, with an extremely high GWP despite being emitted in smaller quantities.
5. **Perfluorocarbons (PFCs)** — by-products of certain industrial processes (e.g. aluminium production), also with a very high GWP.
6. **Sulphur hexafluoride (SF₆)** — used in the electricity industry as an insulator; it is the most potent greenhouse gas per unit of mass and extraordinarily persistent (thousands of years).

An interesting detail: **water vapour**, although it is the most abundant natural greenhouse gas and the most influential on warming, is not included in this official list, because its cycle is governed by natural mechanisms (evaporation/condensation) rather than by direct anthropogenic emissions.

To compare the relative impact of these gases, the **Global Warming Potential (GWP)** is used, which expresses the greenhouse effect of a given mass of gas relative to the same mass of CO₂ over a specified time horizon (typically 20 or 100 years). This is why we speak of tonnes of CO₂ equivalent.

Since the beginning of the Industrial Revolution, the atmospheric concentration of carbon dioxide has risen from around 280 parts per million (ppm) to over **425 ppm**, a level unprecedented in the last several hundred thousand years. Meanwhile, global average temperature has already exceeded the pre-industrial level by about **1.3°C**, while numerous months in recent years have temporarily crossed the 1.5°C threshold, highlighting the acceleration of the warming process.



Atmospheric CO₂ concentration and global temperature anomaly, 1850-2025 (illustrative representation of trends; data updated from the 2016 edition, which stopped at 2014 and at around 400 ppm).

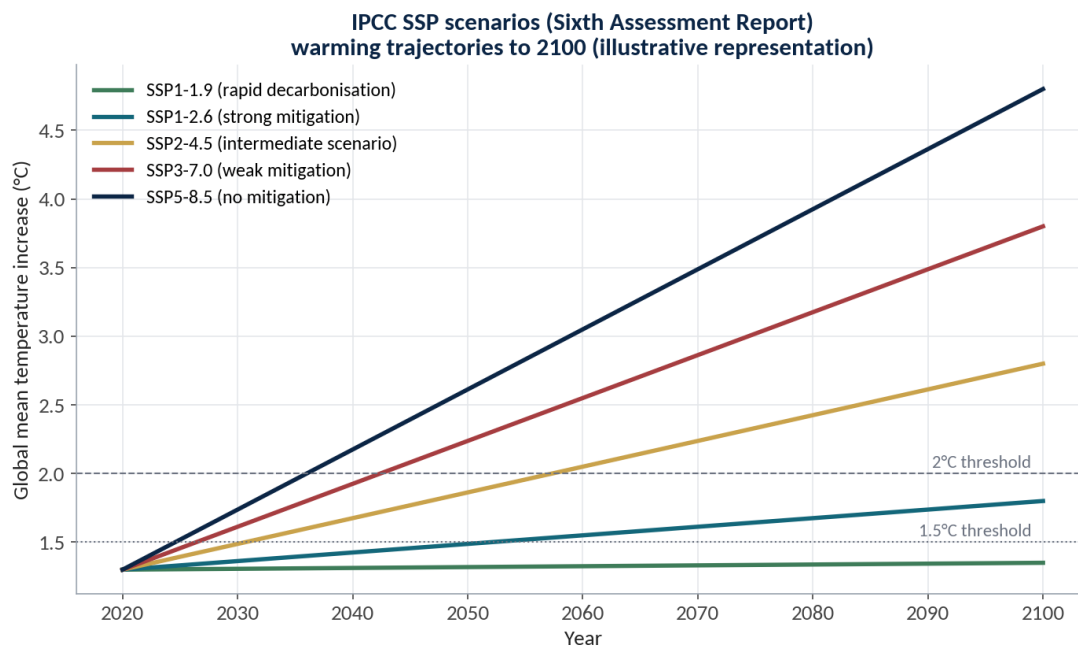
The rise in temperature is not evenly distributed. Polar regions are warming much faster than the global average, with profound changes in the extent of Arctic sea ice, the melting of mountain glaciers and the stability of the Greenland and West Antarctic ice sheets. The oceans absorb more than 90% of the excess heat accumulated by the climate system, causing thermal expansion of seawater, a rise in mean sea level and increasing acidification.

As in the original edition, the **inertia of the climate system** remains crucial: carbon dioxide remains in the atmosphere for extremely long periods (it is still estimated to take on the order of several decades before partial reabsorption by the oceans and biosphere, and centuries before a lasting return towards previous climate conditions), which makes the timeliness of mitigation policies particularly important.

Not all greenhouse gases have the same effect: methane (CH₄) and nitrous oxide (N₂O), although present in smaller quantities than CO₂, have a much higher global warming potential (**Global Warming Potential, GWP**) per unit of mass. GWP is a relative, dimensionless measure that takes into account both the intensity of a gas's greenhouse effect and its rate of decay in the atmosphere. In international regulatory practice, the 100-year GWP (GWP100) is still predominantly used, while for methane reduction policies the GWP20, which gives greater weight to short-term climate effects, is gaining importance — methane, with a GWP100 of around 28-30 but a GWP20 of over 80, illustrates well why the choice of time horizon is not neutral in setting policy priorities.

2.2. From RCP scenarios to SSP scenarios

The original edition used the **Representative Concentration Pathways (RCP)** scenarios, developed for the IPCC Fifth Assessment Report and distinguished according to the intensity of the climate policies adopted. The Sixth Assessment Report introduced a new family of scenarios, the **Shared Socioeconomic Pathways (SSP)**, which combine different pathways of economic, demographic, technological and political development with different emission trajectories, making it possible to represent not only greenhouse gas concentration levels but also the differing capacity of societies to adapt to climate change.



IPCC SSP scenarios (Sixth Assessment Report): warming trajectories to 2100 (illustrative representation). Only the most aggressive mitigation scenarios (SSP1-1.9 and, in part, SSP1-2.6) are compatible with the 1.5-2°C target.

One of the key messages of AR6 is that every additional fraction of a degree matters: climate impacts do not increase linearly but tend to become progressively more severe as global average temperature rises. Even seemingly small differences, for example between 1.5°C and 2°C, lead to significant changes in the frequency of extreme events, biodiversity loss, the availability of water resources and sea-level rise.

2.3. The carbon budget and tipping points

A concept that has become increasingly central is the **carbon budget**: the cumulative amount of CO₂ that can still be emitted while maintaining a given probability of limiting global warming to a set threshold. The carbon budget has changed the way climate policy is interpreted: what matters is no longer only the annual level of emissions, but their cumulative total over time. Every tonne of CO₂ emitted reduces the residual budget available for subsequent years — a constraint that, according to the IPCC's most recent estimates, is now much tighter than it was ten years ago, since a significant share of the budget compatible with 1.5°C has already been used up.

The IPCC also highlights the growing risk associated with so-called **tipping points**, thresholds beyond which certain natural systems could undergo rapid, irreversible or hardly reversible changes: the destabilisation of the Greenland and West Antarctic ice sheets, the degradation of the Amazon rainforest, the thawing of permafrost²

² Ground that remains permanently frozen (for at least two consecutive years), typical of Arctic and sub-Arctic regions (Siberia, Alaska, northern Canada). It matters for the climate for a specific reason: it contains enormous quantities of trapped organic carbon — plant and animal remains accumulated over millennia which, having remained frozen, have never decomposed.

The problem is that global warming is progressively thawing this ground. When it thaws, micro-organisms resume decomposing the organic matter, releasing CO₂ and above all methane (the most potent greenhouse gas in the short term). This creates a classic positive feedback loop: the more the permafrost thaws, the more greenhouse gases are released, the more the temperature rises, the more the permafrost thaws — a self-reinforcing mechanism that is therefore considered one of the “non-linearity” risks.

and the possible slowdown of the Atlantic thermohaline circulation³. These phenomena are of growing interest to finance as well, as they introduce systemic risks that are difficult to insure and characterised by highly asymmetric probability distributions; the increasing attention paid by central banks and supervisory authorities to **climate risk** reflects precisely this development, which now treats the climate scenario as a macro-financial variable capable of affecting the stability of the entire financial system.

2.4. Environmental and economic impacts, mitigation and adaptation

Valuing climate change damages in monetary terms remains a complex exercise for four reasons: the global nature of the problem in contrast with strongly regional and sectoral impacts (the atmosphere is a public good); the high uncertainty of projections; the length of the time horizons involved, which makes the discount rate adopted crucial — and controversial; and finally ethical issues that escape monetisation. Available estimates continue to indicate that the burden of climate change will not be shared equally: the poorest economies of Africa and South-East Asia remain the most exposed, owing to their greater dependence on natural resources, their lower capacity to rebuild capital destroyed by extreme events and a more general “development deficit” that adds to the climate adaptation deficit.

There are two broad families of response to climate change:

- **Mitigation:** reducing greenhouse gas emissions at source. It is the only strategy capable of tackling the problem at its root and generates non-excludable global benefits, but it requires international coordination that is difficult to achieve (risk of *free-riding*, since the atmosphere is a public good) and does not produce immediate benefits.
- **Adaptation:** measures that reduce the impact of damage already occurring or expected (for example drought-resistant crops, early warning systems). It is typically local, less subject to the *free-riding* problem, often cheaper in the short term and provides immediate protection — but it does not reduce atmospheric concentrations, involves uncertainty about its actual effectiveness, and can reinforce inequalities, being a “private good”.

Mitigation and adaptation remain complementary strategies, joined in recent years by the concept of **climate resilience**, which combines the two dimensions with the capacity of economic and social systems to absorb climate shocks, recover quickly and transform in response to increasingly frequent extreme events. For institutional investors, this means that project appraisal can no longer be limited to expected cash flows, but must also incorporate the **physical risk** of climate change, the **transition risk** arising from new environmental policies and the **liability risk** (*liability risk*) linked to growing climate litigation — three risk categories that will be revisited in Chapter 4 and that now structurally shape investment analysis by banks and institutional investors.

³ A system of ocean currents — of which the Gulf Stream is the best-known part — that carries warm, salty water from the tropics towards the North Atlantic at the surface, and cold, dense water in the opposite direction at depth. The engine of this “conveyor belt” is the difference in water density (hence “thermo-haline”: temperature + salinity). This circulation is crucial for the European climate: it is one of the reasons why Western Europe has a much milder climate than regions at equivalent latitudes in North America or Asia. The risk, widely discussed in the scientific literature, is that melting Greenland ice will release large quantities of fresh water into the North Atlantic, reducing the density of surface water and weakening (or, in the extreme case, halting) this circulation — with potentially drastic consequences for Europe’s regional climate, over a relatively short period on a geological scale. Both are textbook examples of the type of risk involved: once a certain temperature threshold is crossed, these mechanisms can be triggered abruptly and in a way that is difficult to reverse, unlike the more predictable “linear” warming on which most of the economic models presented in the book are based.

In Focus: Private goods and public goods

In environmental and resource economics, understanding the characteristics of natural assets is essential for designing effective regulation. Environmental goods are often classified according to two sets of criteria: (i) rival and non-rival, and (ii) excludable and non-excludable.

A rival good is one whose consumption by one person reduces consumption by others. Any finite, scarce and exhaustible good can be considered rival, such as fish stocks, livestock, land and forests.

An excludable good can be privatised, in the sense that outsiders can be prevented from accessing it. In theory, anything can be made excludable through an adequate level of control. In practice, high transaction and monitoring costs, international or global jurisdictions, an inadequate legal system and the lack of property rights favour the existence of non-excludable goods, such as air or international waters.

Goods with characteristics at the intersection of the two sets of criteria are known as: (i) private goods, (ii) club goods, (iii) common goods, and (iv) public goods.

- **Private goods** are goods that are both rival and excludable. Agricultural capital (livestock, land) and productive capital (machinery, financial capital) are all private goods. Private goods are at the heart of the Coase theorem on market equilibrium, since they can be individually identified, monetised and traded.
- **Club goods** are excludable but non-rival. Access to them can be restricted, but each member's consumption has no impact on the consumption of others. This category includes service and network assets, such as research and development (R&D), satellite imagery, the internet and broadcasting. In some cases (the internet, for example), non-rivalry depends heavily on the number of users and the intensity of use: when pressure on the service becomes too high, the good reverts to being private or common, depending on whether the service can be individualised.
- **Common goods** are both rival and non-excludable, giving rise to what is often called "the tragedy of the commons", i.e. an overexploitation of resources that ends in their complete degradation. Common goods are particularly relevant in environmental and resource economics, above all because it is difficult and costly to monitor the consumption of scarce natural resources not associated with property rights. The degradation of forests and land or the depletion of fish stocks are well-known examples of the problem.
- **Public goods** are non-excludable and non-rival, which makes them particularly exposed to the free-riding problem and to a lack of effective coordination. A prime example of a public good is the atmosphere.

These concepts will be revisited in Chapter 4.

3. International efforts to tackle climate change and the evolution of carbon markets

In the ten years following the Kyoto Protocol, international climate governance underwent an extraordinary evolution, and carbon markets moved from experimental environmental policy tools to structural components of economic, industrial and financial decarbonisation strategies. This chapter therefore provides the institutional foundation of the sector.

3.1. It all starts with the IPCC

International climate governance began in 1988 with the establishment of the IPCC (**I**nter**g**overnmental **P**anel on **C**limate **C**hange).

It is the United Nations scientific body tasked with gathering, assessing and synthesising the world's scientific knowledge on climate change. It does not conduct its own original research, but reviews the existing scientific literature and produces synthesis reports for policymakers.

It was established within the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO), in response to the growing international attention to climate issues that had emerged as early as the 1979 World Climate Conference in Geneva.

What it does in practice:

- It periodically publishes **Assessment Reports** — the first in 1990, the fifth in 2013-2014
- The **First Assessment Report (1990)**, based on the work of some 400 scientists, established that global warming was a real problem caused by anthropogenic greenhouse gas emissions, and led directly to the creation of the UNFCCC in 1992
- It develops reference scenarios such as the **RCPs** (Representative Concentration Pathways) discussed in chapter 2
- It provides **Global Warming Potential (GWP)** estimates for the various greenhouse gases

The IPCC is the scientific and institutional reference point around which the entire climate governance architecture described in this chapter has been built — from the UNFCCC to the Kyoto Protocol and the subsequent Conferences of the Parties (COPs). It is also the most frequently cited source for data on CO₂ concentrations, temperatures and emission scenarios.

Although there are minority “sceptical” positions, the scientific consensus represented by the IPCC is broad, and the most recent observations tend to confirm the more worrying scenarios rather than refute them.

3.2. From the Rio Convention to the Paris Agreement

International cooperation on climate change is founded on the **United Nations Framework Convention on Climate Change (UNFCCC)**, adopted at the Rio de Janeiro Earth Summit in 1992 and in force since 1994. The Convention did not set binding quantitative emission-reduction targets, but introduced the principle of **Common but Differentiated Responsibilities and Respective Capabilities (CBDR-RC)**, according to which all States share responsibility for tackling climate change, but that responsibility must be modulated according to historical contribution to emissions, level of economic development, technological capabilities and available financial resources — a principle that still represents one of the central elements of climate negotiations today.

The countries party to the Convention were classified into three categories: Annex I countries (OECD industrialised countries and economies in transition of Central and Eastern Europe), Annex II countries (the subset of Annex I

excluding countries in transition, required to finance climate action in developing countries) and Non-Annex I countries (developing countries, with no reduction obligations).

The Convention's decision-making body is the **Conference of the Parties (COP)**, which brings together all member States annually. Over the years, the COPs have taken on an increasingly important role in shaping global climate policy, as summarised in the following table.

COP	Year	Main outcomes
COP3 — Kyoto	1997	Adoption of the Kyoto Protocol
COP15 — Copenhagen	2009	First political recognition of the 2°C target
COP21 — Paris	2015	Adoption of the Paris Agreement
COP26 — Glasgow	2021	Glasgow Climate Pact; completion of the Article 6 rulebook
COP27 — Sharm el-Sheikh	2022	Establishment of the Loss and Damage Fund
COP28 — Dubai	2023	First Global Stocktake; recognition of the transition away from fossil fuels
COP29 — Baku	2024	Strengthening of international climate finance
COP30 — Belém	2025	Update of NDCs and launch of the new cycle of climate targets

Table 1. Historical evolution of the COPs.

The first true international agreement with quantitative emission-reduction targets was the **Kyoto Protocol** (1997, in force since 2005), which introduced legally binding emission limits for industrialised countries (Annex I) and the first carbon market mechanisms — *International Emissions Trading*, the *Clean Development Mechanism* (CDM) and *Joint Implementation* (JI). More specifically:

- Emissions Trading (Art. 17): Annex I countries can trade their assigned emission allowances (Assigned Amount Units, AAUs) among themselves.
- Clean Development Mechanism – CDM (Art. 12): an Annex I country finances an emission-reduction project in a Non-Annex I country, obtaining credits (Certified Emission Reductions, CERs) that can be used towards its own target. It is the only mechanism that creates new credits, since the host country has no emission cap of its own.
- Joint Implementation – JI (Art. 6): similar to the CDM, but between two Annex I countries (typically an investment in an economy in transition); it generates Emission Reduction Units (ERUs) and, since it does not create new credits in addition to the total, requires a leaner verification process.

The system is overseen by an infrastructure of national registries linked to an international transaction registry (International Transaction Log), which verifies in real time that each transaction complies with the Protocol's rules.

Kyoto nevertheless had important structural limitations: its obligations applied mainly to advanced economies, while the growth of China, India and numerous other emerging economies radically changed the global distribution of emissions, making a system built on a rigid distinction between developed and developing countries increasingly ineffective. These shortcomings led to the adoption of the **Paris Agreement** at COP21 in December 2015.

The Paris Agreement represents the most important change in international climate governance since the creation of the UNFCCC. Unlike Kyoto, it does not assign predetermined emission allowances to individual States: instead,

each country submits its own **Nationally Determined Contributions (NDCs)**, in which it independently sets its reduction targets and the policies needed to achieve them, with a five-yearly review mechanism requiring each new cycle to represent an improvement on the previous one. The central objective is to keep the temperature increase well below 2°C, pursuing efforts to limit it to 1.5°C, and to achieve a balance between anthropogenic emissions and removals in the second half of the century — the concept now commonly referred to as **Net Zero**.

Collective progress towards these objectives is measured through the **Global Stocktake**, a five-yearly review mechanism introduced by the Paris Agreement. The first Global Stocktake, concluded at COP28 in Dubai in 2023, showed that, although significant progress has been made in deploying renewable energy, the commitments made by States as a whole are still insufficient to keep warming within 1.5°C — a conclusion that reinforced the need for more ambitious NDCs in the following negotiating cycle.

Article 6 and the new generation of international carbon markets

Among the most economically significant aspects of the Paris Agreement is **Article 6**, devoted to international cooperation through market instruments, whose implementing rulebook was completed at COP26 in Glasgow. Article 6.2 allows States to transfer mitigation outcomes directly to one another (*Internationally Transferred Mitigation Outcomes*, ITMOs), provided that each transfer is accompanied by a **Corresponding Adjustment** that avoids double counting of the same reduction — the *no double counting* principle is now one of the fundamental elements of the entire architecture of international carbon markets. Article 6.4 establishes a new multilateral mechanism supervised by the United Nations, intended to progressively replace the Clean Development Mechanism provided for under Kyoto, with much more rigorous criteria for additionality, permanence, monitoring and independent verification. Finally, Article 6.8 covers forms of international cooperation that do not involve market instruments (technology transfer, capacity building, financial support).

3.3. The global expansion of Emission Trading Systems and the dominant role of the EU ETS

Economic theory identifies three broad categories of instruments through which governments can reduce emissions: regulatory instruments (*command and control*), fiscal instruments (carbon tax) and market instruments (Emission Trading Systems – ETS). In an ETS, the public authority sets the total quantity of emissions allowed (the **cap**), divides it into tradable permits — allocated free of charge, auctioned or bought on the secondary market — and lets the market determine the price. Companies with lower abatement costs reduce their emissions and sell their surplus allowances; those with higher costs buy allowances on the market: in this way, reductions are made where they are economically least costly.

While in the early 2000s the EU ETS was essentially the only large regulated carbon market, today numerous jurisdictions have introduced their own systems, as summarised in the following table.

ETS	Launch	Main sectors covered
European Union ETS	2005	Energy, industry, aviation, maritime transport
Swiss ETS	2008	Industry and energy
New Zealand ETS	2008	Most of the economy
RGGI (USA, North-East)	2009	Power generation
California Cap-and-Trade	2013	Energy, industry, transport
Québec ETS	2013	Regional economy

ETS	Launch	Main sectors covered
Korea ETS	2015	Industry and energy
China National ETS	2021	Power generation, expanding
UK ETS	2021	Energy and industry

Table 2. Evolution of ETSs in various countries.

Among all these systems, the **European Union Emissions Trading System (EU ETS)**, established in 2005, holds a dominant position: it is the oldest regulated carbon market, the most liquid and the main global benchmark for CO₂ price formation. Its evolution can be divided into four phases. In **Phase I (2005-2007)**, an experimental phase, excessive free allocation of allowances produced a surplus and a price collapse, but made it possible to develop the market infrastructure. In **Phase II (2008-2012)**, which coincided with the first Kyoto commitment period, the global financial crisis reduced industrial output and demand for allowances, generating a new surplus. **Phase III (2013-2020)** marked the real turning point, with auctioning as the main allocation mechanism, European harmonisation and, above all, the introduction in 2019 of the **Market Stability Reserve (MSR)**, the automatic mechanism that temporarily withdraws allowances from the market when the surplus exceeds certain thresholds and releases them in the event of scarcity, stabilising supply and strengthening the credibility of the price. **Phase IV (2021-2030)**, still under way, has brought a strengthening of the cap's linear reduction factor, the progressive phase-out of free allowances, integration with the **Carbon Border Adjustment Mechanism (CBAM)**, extension to maritime transport and the creation of **ETS2**, the new market — separate from and not fungible with EUAs — covering buildings and road transport (sectors not included in the current ETSs, see Table 2).

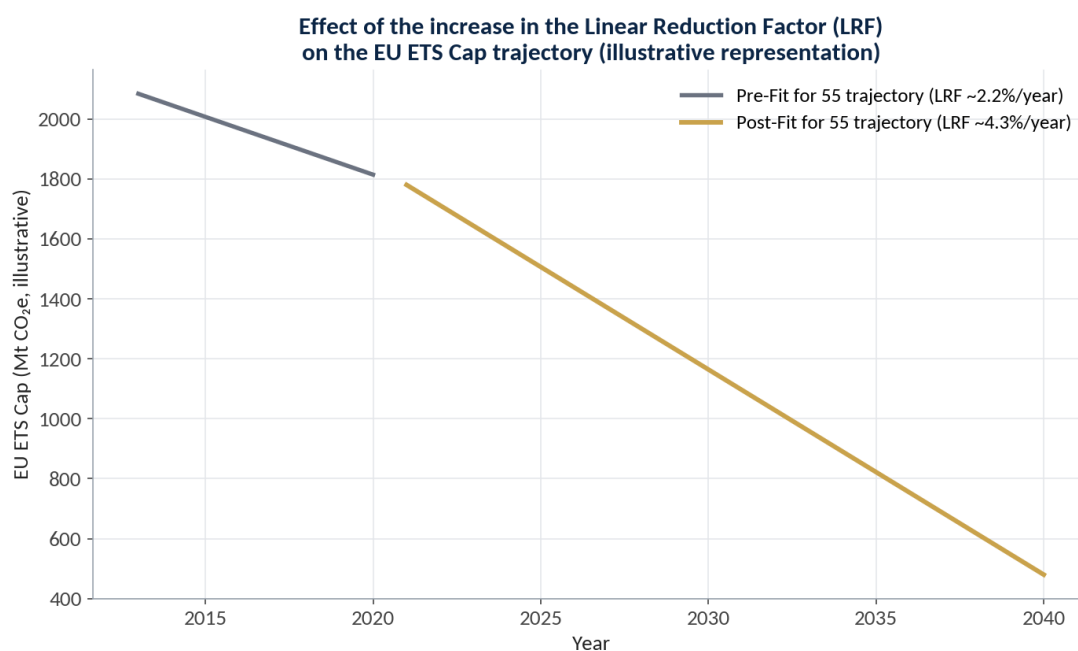


Figure 1. Effect of the increase in the Linear Reduction Factor (LRF) adopted under the Fit for 55 package on the EU ETS Cap trajectory (illustrative representation): the annual reduction in the number of available allowances has more than doubled compared with previous phases.

The evolution of the EU ETS cannot be understood without considering the **Carbon Border Adjustment Mechanism (CBAM)**. The steady rise in the price of European allowances exposes EU companies to the risk of **carbon leakage** — the relocation of production to countries with less stringent climate regulation. CBAM addresses this risk by progressively applying a carbon price to imports of cement, steel, aluminium, fertilisers,

electricity and hydrogen (whose production releases greenhouse gases) from countries without equivalent systems, and is set to gradually replace the previous system of free allocation, while strengthening incentives to decarbonise outside the European Union as well.

One of the most significant developments of the past decade concerns precisely the change in the economic role of the CO₂ price: from a marginal regulatory cost, as it was perceived in the early phases of the EU ETS, to a fundamental economic variable that influences investment in renewables, the competitiveness of different power generation technologies, the economic appraisal of carbon capture and storage plants (CCS/CCUS) and the value of numerous energy assets. The carbon market is no longer just an environmental policy tool, but a permanent feature of the European economic system — a theme that will be taken up and explored in depth, from a strictly financial perspective, in Chapters 7 and 8.

3.4. Guarantees of Origin: an environmental market without a cap

Alongside the cap-and-trade systems described above there is another family of environmental markets, conceptually similar but structurally different: **Guarantees of Origin** (*Guarantees of Origin*, GOs). These are electronic certificates, regulated in Europe by the Renewable Energy Directive, which certify that a given quantity of electricity (typically one megawatt-hour) has been produced from renewable sources. Every time a wind, solar or hydroelectric plant feeds energy into the grid, it receives a corresponding GO, which can be traded separately from the underlying physical energy: a company wishing to declare “100% renewable” energy consumption buys and cancels a number of GOs equal to its requirements, regardless of the energy mix it actually receives from the grid.

The mechanism shares with the EU ETS the principle of separating (*unbundling*) an environmental attribute from the physical good with which it is associated — in the case of emission allowances, the “right to pollute”; in the case of GOs, the “renewable quality” of the energy. The substantial difference, however, is that Guarantees of Origin do not stem from a cap imposed by a regulatory authority: anyone producing renewable energy automatically receives the corresponding certificate, without any aggregate scarcity constraint. The price of GOs therefore mainly reflects the balance between the renewable capacity installed in a given country and year (supply) and the reporting obligations or voluntary sustainability commitments of buying companies (demand) — not, as in the case of EUAs, the probability of exceeding a physical emission limit set by decree. For this reason, Guarantees of Origin have historically traded at much lower prices and with far less tight dynamics than EU ETS allowances: they are an environmental market in their own right, but lack the controlled-scarcity mechanism that is the distinctive feature — and the main lever of effectiveness — of cap-and-trade systems.

3.5. Voluntary carbon markets

Alongside regulated *Emission Trading* systems, a second major segment of the global carbon market has developed over the past fifteen years: **Voluntary Carbon Markets (VCM)**. Unlike compliance systems, voluntary markets allow companies, public bodies and investors to buy **carbon credits** to voluntarily offset part of their residual emissions, in projects involving reforestation, ecosystem conservation, renewable energy, methane recovery from landfills, regenerative agriculture and, more recently, technologies for the direct removal of CO₂ from the atmosphere (*Direct Air Capture*). The growth of VCMs has been driven by the spread of corporate Net Zero targets and investors’ growing attention to ESG criteria.

The rapid expansion of voluntary markets has, however, revealed significant problems relating to the quality and environmental credibility of the credits generated, in particular with respect to four requirements: **additionality** (the reduction must be additional to the baseline scenario), **permanence** (reductions must not be reversed by

subsequent events, such as fires in the case of forestry projects), absence of **leakage** (a reduction in one area must not translate into an increase elsewhere) and **verifiability** by independent bodies. International standards such as Verra’s **Verified Carbon Standard (VCS)**, the **Gold Standard**, the **American Carbon Registry** and the **Climate Action Reserve** have progressively strengthened their methodological criteria, partly in response to criticism of the quality of some credits generated in the early stages of the market’s development.

It is important not to confuse the EU ETS with voluntary markets: they are profoundly different instruments, as summarised in the following table.

Feature	European Union Allowances (EUAs)	Voluntary carbon credits
Nature	Emission allowances	Certified reductions/removals
Market type	Regulated (cap-and-trade)	Voluntary
Issuer	Public authority (EU)	Certified private projects
Use	Regulatory compliance obligations	Voluntary offsetting
Price formation	Supply/demand within the EU ETS	Project quality and ESG demand

Table 3. Comparison between EUAs and carbon credits on voluntary markets (VCM).

3.6. In focus: the concept of additionality

The additionality principle is the cornerstone requirement on which the entire *Clean Development Mechanism* rests: an emission reduction can generate CERs only if it would not have occurred in a “business as usual” baseline scenario, i.e. in the hypothetical world in which the project had not received carbon-credit-related funding. If this condition is not met — if the project would have been carried out anyway, because it was economically viable in its own right or required by local regulation — the issuance of the corresponding credits does not correspond to any real and additional reduction in global emissions: the Annex I country buying those credits will still obtain the right to emit more elsewhere, while in the host country nothing will actually have changed compared with the baseline. The net result is, paradoxically, an implicit widening of the system’s aggregate emissions cap rather than a reduction.

The problem is: how can the regulator know that the emission reduction would not have happened anyway? Suppose Italy finances a wind farm in India, or Switzerland finances a methane capture plant at a landfill in Brazil. If the Indian wind farm or the Brazilian plant would have been built anyway — because they were already economically viable, or because they were required by local law — then issuing CERs for those projects does not reduce net global emissions at all. Italy and/or Switzerland (Annex I countries) will acquire those credits and use them to emit more greenhouse gases, while India and Brazil would have reduced their emissions anyway. The net result is an increase in global emissions, not a reduction: a “phantom” credit has simply been created that allows more pollution without anything actually changing in the real world.

A project is “additional” if it meets this condition: the emission reduction it generates would not have occurred in a “business as usual” reference scenario (baseline) — that is, in the counterfactual scenario in which the project does not receive CDM funding.

Put another way: CDM funding must have been the decisive factor that made the project possible or viable, not an additional reward for something that would have happened anyway.

Verifying additionality poses an intrinsic methodological difficulty, since it requires demonstrating a counterfactual — a scenario that, by definition, will never be observed because the project has been carried out. The methodologies approved by the CDM Executive Board address the problem through standardised tests that check for the existence of

- economic/financial barriers: without the additional revenue from CERs, the project's financial return is below the market threshold (the classic “investment analysis”).
- technological barriers: the project uses a technology not yet widespread in the local context, with technical risks that would discourage its spontaneous adoption.
- common practice barriers: it is shown that similar projects are not yet widespread in the region or sector, as evidence that they are not “the norm”.

These tests, however, rely largely on information provided by the project proponent itself, which has a direct economic interest in presenting the project as marginal relative to the viability threshold — a classic case of information asymmetry that makes verification structurally vulnerable.

The importance of additionality in this context stems from three considerations. First, the CDM is the only one of Kyoto's three flexible mechanisms that creates new credits rather than simply transferring existing permits between parties subject to a common cap: an additionality error therefore translates directly into a loosening of the global aggregate constraint, not a mere redistribution. Second, systemic doubt about the additionality of a significant share of registered projects helps explain the persistent discount at which CERs have historically traded relative to European EUAs, since the market also prices in this specific risk, alongside the country, regulatory and validation risks already inherent in every CDM project. Third, the mechanism suffers from a structural adverse selection problem: the most financially sound projects, and therefore the most attractive to investors, are also those most likely to have been feasible anyway without CDM support — and therefore the least additional — while projects whose additionality is easiest to demonstrate tend to be the least attractive in terms of financial risk.

Independent studies (research by the European Commission, Cames et al. 2016, and others) have estimated that a significant share of registered CDM projects — according to some analyses, even the majority — had questionable additionality or additionality that could not be convincingly demonstrated. This is one of the reasons why, in the design of subsequent carbon market mechanisms (such as the Paris Agreement and its Article 6), efforts were made to introduce more stringent and verifiable additionality criteria, together with automatic correction mechanisms such as the *Long-term Average Baseline* or “ineligibility” thresholds for technologies that are now mature (such as large-scale wind power, which is today generally considered non-additional in many markets, having reached grid parity).

3.7. Outlook and conclusions

Developments observed up to 2026 suggest a number of long-term trends: further geographical expansion of carbon pricing systems, often inspired by the European model; growing integration between climate policy, industrial policy and international trade, of which CBAM is probably the first fully-fledged example; a growing role for financial investors, who now regard emission allowances as a genuine **environmental asset class**; and finally the possibility, still debated, of progressive integration (*linking*) between the various regional and national ETSs

towards a more global carbon market, for which Article 6 of the Paris Agreement provides a reference framework but not yet full implementation.

In short, over little more than thirty years, international climate governance has evolved from a set of general principles of cooperation into a complex system that integrates international treaties, regulated markets, voluntary mechanisms, financial instruments and industrial policies. The Paris Agreement was the turning point in this process, while the expansion of ETSs — and, in particular, the evolution of the EU ETS — has consolidated the role of carbon pricing as a central instrument of the transition to a low-emission economy. Born as simple administrative permits, **European Union Allowances (EUAs)** are now used not only by companies subject to EU ETS obligations, but also by financial intermediaries, institutional investors and specialised risk-management operators: a transformation that calls for a specific analysis, to which Chapters 7 and 8 of this volume are devoted.

4. The economics of climate change mitigation

“Climate change, like other environmental problems, involves an externality: the emission of greenhouse gases damages others at no cost to the agent responsible for them” (Nicholas Stern). This chapter examines the three classic instruments through which environmental policy can correct this externality — taxes, tradable permits and subsidies — comparing them in terms of efficiency, information requirements and behaviour under uncertainty. The second part of the chapter illustrates the applied framework, showing how these same instruments have been translated in practice, in Europe, into an industrial policy of historic scope.

4.1. Emissions as an externality

When a firm decides how much to produce, it maximises its profit by comparing marginal revenue with private marginal cost: as long as the revenue from an additional unit exceeds its cost, it pays to produce it. But production also generates a social cost — emission damage — which the firm does not bear directly and therefore ignores. The result is an output higher than the socially optimal level: the firm stops where marginal revenue equals private marginal cost alone, whereas the optimal level for society lies where marginal revenue equals total marginal cost (private plus social), a lower level of output.

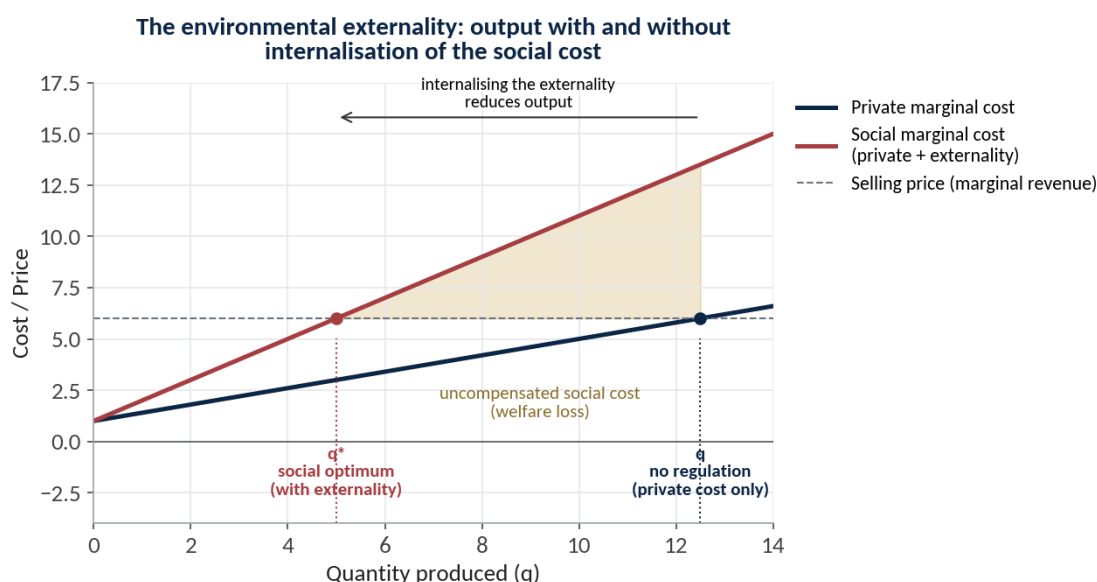


Figure 2. If the firm considers only its own private marginal cost, it produces a quantity above the socially optimal level q^* , which would be achieved by also internalising the social marginal cost (externality).

All environmental policy can be read as an attempt to close this gap, “internalising” into the firm’s calculation the social cost that would otherwise remain external to its decisions. The key concept for quantifying this cost today is the **Social Cost of Carbon (SCC)**, which measures the monetary value of the total economic damage caused by emitting one additional tonne of CO₂ — damage to productive activities, loss of labour productivity, health costs, impacts on ecosystems, agricultural losses and extreme weather events. Estimates of the SCC depend on highly uncertain factors (future emission trends, climate sensitivity, discount rate, adaptive capacity), which is why the literature presents widely varying estimates; the general trend in recent years, however, has been to recognise significantly higher values than the assessments available in the early 2000s, reflecting greater scientific understanding of long-term climate risks.

4.2. Taxes and subsidies

The solution proposed by the economist Pigou (1918) is to impose a tax per unit of output (or of pollutant emitted) exactly equal to the social marginal cost at the optimum: in this way, the private marginal cost perceived by the firm converges towards the social one, and output falls to the optimal level. The practical limitation of this solution is that it requires the regulator to have almost perfect knowledge of both the firm's private marginal cost curve and the social damage curve — information rarely available with precision.

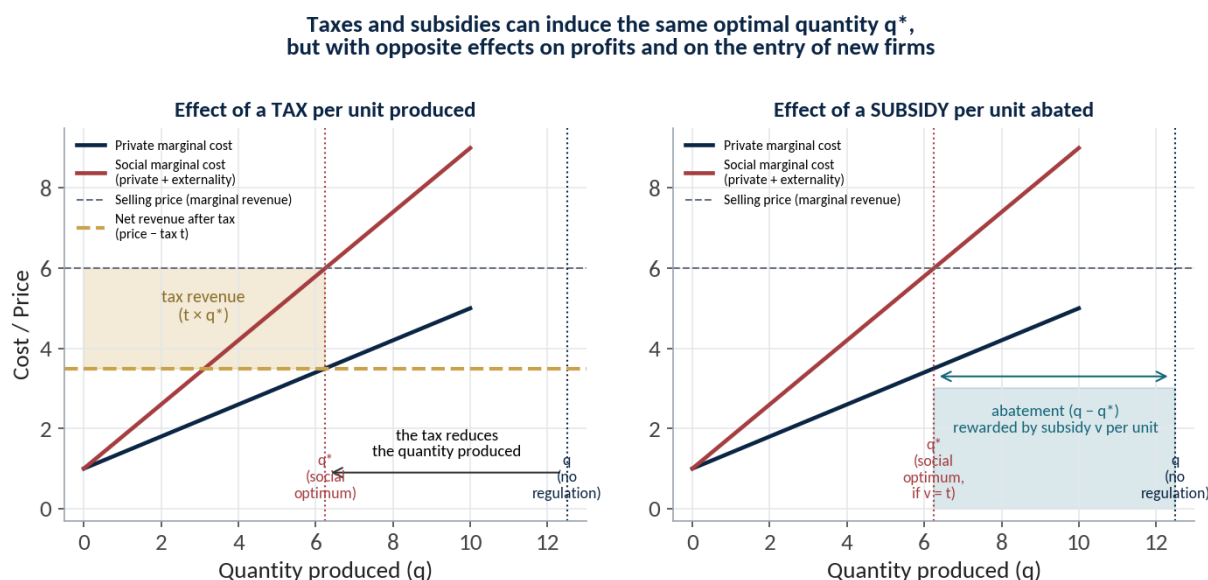


Figure 3. Internalisation of social costs: this can be achieved either through a tax (left-hand chart) or through a subsidy (right-hand chart).

A subsidy per unit of emissions avoided can in theory produce the same incentive effect as a tax of the same amount, but in practice taxes and subsidies have opposite effects on profitability (the former reduces it, the latter increases it): a subsidy can therefore attract new entrants into the sector and, paradoxically, increase total output and emissions. In the dynamics of the transition to clean technologies, relying on the carbon price alone to achieve the same technological substitution attainable with a combination of subsidies and permits would require a carbon price several times higher in the early years of the transition — an argument in favour of using the two instruments together, especially in the early stages of emerging technologies. Let us look at this point more closely.

Imagine an energy sector that has to switch from coal (a “dirty”, mature, cheap technology) to a clean technology that is still young — say wind or solar in the early 2000s. In that initial phase the clean technology is still inefficient: it costs more per unit of energy produced, simply because it has not yet accumulated the experience, economies of scale and incremental improvements that come only with large-scale use (so-called *learning-by-doing*: the more a technology is produced and installed, the better and cheaper it becomes — the same mechanism that makes photovoltaics much cheaper today than 20 years ago).

If the carbon price (a tax on emissions, or its equivalent through permits) is the only climate policy instrument, then to persuade an investor to choose the clean technology instead of coal, the additional cost imposed on coal (by the carbon price) must be sufficient to offset the cost disadvantage that the clean technology has **at that specific moment**, when it is still immature. But precisely because that disadvantage is large at the outset, the

carbon price needed to tip the economics in favour of clean technology must be equally large — that is, “several times higher” than would be needed once the clean technology had become more mature and competitive.

It is a bit like asking a single instrument to do two jobs at once: penalise the dirty technology **and** single-handedly close the entire technological maturity gap of the clean one. The carbon price needed to achieve this double effect in the very first years of the transition would be politically and economically very burdensome — consider how high a carbon tax would have had to be to make 2005 photovoltaics competitive with coal, when panels cost several times what they cost today.

A direct subsidy to the clean technology (for example to R&D investment, or to renewable energy production) tackles the problem from the opposite side: instead of **penalising** the dirty technology until it offsets the entire disadvantage of the clean one, it **directly reduces** that disadvantage, artificially lowering the cost of the clean technology while it accumulates experience and gradually becomes more efficient on its own. In this way, the “work” of making clean technology competitive is shared between two instruments — the carbon price (which penalises the dirty technology) and the subsidy (which helps the clean one) — and neither has to be set at an extreme level.

As the clean technology matures and its cost falls naturally, thanks in part to learning-by-doing, the gap to be closed narrows, and the carbon price alone once again becomes a sufficient instrument — there is no longer any need to combine it with a massive subsidy. This is why the book presents the tax/permit + subsidy combination not as a permanent solution but as a transitional measure, justified precisely by the dynamic (technological learning) characteristics of emerging technologies in their early years.

4.3. Tradable permits, the Coase theorem and cap-and-trade

The economist Coase (1960) proposed an alternative to the Pigouvian tax: if property rights over pollution are well defined and tradable, the polluting firm and the injured parties can bargain freely until they reach the same socially optimal level of pollution, regardless of who initially holds the right. The great advantage of this approach over the tax is that it does not require the regulator to have any prior knowledge of the cost curves: the parties themselves reveal them through negotiation. Applied to a global public good such as the atmosphere, however, the Coase theorem runs into severe practical limitations — the transaction costs of negotiations among billions of parties would be enormous — which is why an institutional compromise is used: the **cap-and-trade** system, in which a central authority sets the overall emissions cap in advance, divides it into tradable permits and lets firms trade them among themselves. In equilibrium, the price of the permit equals the lowest marginal abatement cost available in the system, ensuring that the cap is met at the lowest possible aggregate cost.

4.4. Price or quantity? The Weitzman theorem and uncertainty

A central — and often misunderstood — issue concerns the choice between “price” instruments (taxes) and “quantity” instruments (permits) when abatement costs are uncertain. The Weitzman theorem (1974) shows that the optimal choice depends on the relative steepness of the social marginal benefit and marginal abatement cost curves: if the social marginal benefit is steeper than the marginal abatement cost, an error in estimating costs under a tax regime can lead to emissions far above the optimum, and a quantity instrument (the permit) is therefore preferable; if, instead, the marginal abatement cost is steeper, a rigid cap set incorrectly can impose excessive costs on firms, and a price instrument (the tax), which leaves room for adjustment, is preferable.

Let us explain this concept more clearly with the help of charts (see Figure 4):

The Weitzman theorem: what happens when the regulator misestimates abatement costs

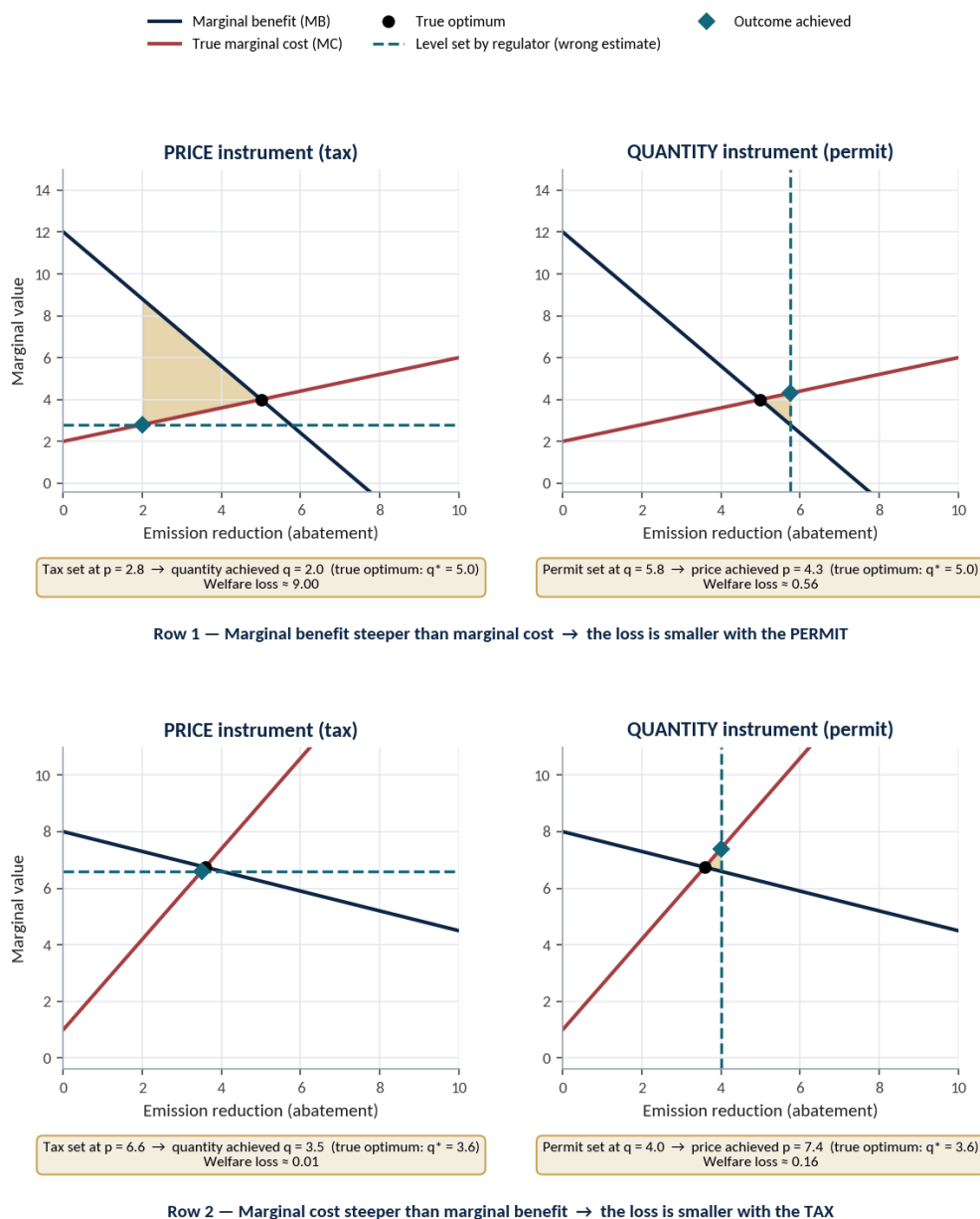


Figure 4. The Weitzman theorem: the choice between tax and permit depends on the relative steepness of the marginal benefit and marginal cost curves when the regulator does not know abatement costs with certainty.

The starting point is the same in both cases: the regulator does not know the true marginal cost curve — it only has an estimate, which is wrong. It must nevertheless choose an instrument: either it sets a price (tax) and lets the quantity abated be determined freely by the market, or it sets a quantity (permit) and lets the price be determined freely.

What happens with the tax (left-hand column): the regulator sets the tax at the level that, according to its wrong estimate, should have produced the optimal abatement. But firms respond to the true marginal cost, not the estimated one: the point where the red line (true cost) crosses the dashed blue line (tax set) determines how much firms will actually abate — a point different from the true optimum (black dot). The orange triangle is the resulting welfare loss.

What happens with the permit (right-hand column): here it is the quantity that is fixed by decree (vertical blue line), whatever the true cost. The permit price adjusts accordingly (where the vertical line crosses the red true-cost line), but the quantity remains the — wrong — one set by the regulator. Here too a loss triangle arises, but of a different size.

Why does the size of the loss change with the slope?

- Upper part of the chart (very steep marginal benefit): when the benefit falls rapidly as abatement increases, a small error in the quantity achieved is very costly in welfare terms (loss ≈ 9.00 with the tax). With the permit, on the other hand, the error is absorbed only by the price — which here can fluctuate considerably without doing too much damage, because the benefit does not depend much on the price itself (loss ≈ 0.56). The permit wins.
- Lower part of the chart (very steep marginal cost): here it is the cost that rises sharply. Fixing a rigid quantity (permit) risks imposing on firms a much higher cost than expected if the estimates were wrong (loss ≈ 0.16). With the tax, on the other hand, firms can freely adjust the quantity abated until the true cost equals the price set — an adjustment that costs very little here (loss ≈ 0.01). The tax wins.

In short: it pays to leave “free to adjust” the variable whose error does the least damage. If getting the quantity wrong is costly (steep benefit curve), it is better to fix the quantity (permit) and let the price adjust; if getting the price/cost wrong is costly (steep cost curve), it is better to fix the price (tax) and let the quantity adjust.

This theoretical insight now finds immediate practical application in the comparison between carbon taxes and Emission Trading Systems, summarised in the following table: the economic literature recognises that there is no universally valid answer, and that the choice depends on the objectives pursued by the legislator — control over the quantity of emissions, typical of ETs, or price stability and predictability, typical of carbon taxes. It is no coincidence that many jurisdictions now adopt hybrid systems.

Carbon Tax	Emission Trading System
Certain price	Certain quantity (cap)
Uncertain level of emissions	Uncertain price, set by the market
Simple administration	Greater operational complexity
Lower volatility	Greater allocative efficiency
Greater fiscal predictability	Possibility of banking/borrowing and hedging

Table 4. Differences between a Carbon Tax and an ETS.

We also examine the distortions that arise when firms have an incentive to manipulate the information they report to the regulator: in the case of free allocation (*grandfathering*), a firm may find it advantageous to overstate its marginal abatement cost in order to obtain more free permits; in the case of an auction without refunds, the opposite incentive leads to understating costs. Montero (2008) proposes an auction mechanism with refunds (*payback*) calibrated to induce firms to reveal their true marginal cost. Finally, cap-and-trade systems are not free of other problems — market manipulation, transaction costs, monitoring difficulties and the risk of *carbon leakage* — a problem which, as seen in Chapter 3, the European Union has recently addressed precisely through the Carbon Border Adjustment Mechanism.

4.5. From carbon pricing to industrial policy: the European Green Deal

Until the mid-2010s, European instruments were mainly geared towards reducing emissions through environmental regulation and the operation of the EU ETS. Since 2019, with the presentation of the **European Green Deal**, climate change has become one of the pillars of the European Union's economic strategy: decarbonisation is no longer regarded solely as an environmental objective, but also as a lever to increase industrial competitiveness, reduce energy dependence, promote technological innovation and attract private investment. One of the most important results of the Green Deal is the **European Climate Law** (2021), which makes legally binding a net emissions reduction of at least 55% by 2030 compared with 1990 levels and climate neutrality by 2050.

To achieve these objectives, the European Commission presented the **Fit for 55** legislative package, the most important piece of European climate legislation since the creation of the EU ETS. Its main innovations include the reform of the EU ETS (faster reduction of the cap, progressive phase-out of free allowances, extension to maritime transport), the introduction of **ETS2** — a second market, separate from and not fungible with EUAs, covering fuels used in buildings and road transport, accompanied by a **Social Climate Fund** designed to mitigate its distributional effects on low-income households — and the **Carbon Border Adjustment Mechanism** described above. These are complemented by industrial policy instruments in the strict sense, such as the **Net Zero Industry Act**, aimed at increasing European manufacturing capacity in strategic transition technologies (photovoltaics, wind, batteries, electrolyzers, heat pumps, CCUS⁴), and the **Critical Raw Materials Act**, devoted to the security of supply of lithium, copper, nickel, graphite and rare earths.

4.6. Climate risk in investment appraisal and sustainable finance

One of the most significant developments in recent years concerns the integration of climate change into financial models. Investors today distinguish three broad categories of risk, already introduced in Chapter 2: **physical risks**, arising from the direct effects of climate change (extreme weather events, wildfires, floods, droughts); **transition risks**, linked to the decarbonisation process (regulatory developments, rising CO₂ prices, obsolescence of emission-

⁴ **CCUS** stands for *Carbon Capture, Utilisation and Storage* — a family of technologies that intercept CO₂ before it is released into the atmosphere (or remove it directly from the air) and then store it permanently or reuse it as a raw material.

Capture — CO₂ is intercepted at source, typically in emission-intensive industrial plants (coal/gas power plants, cement works, steelworks, chemical plants) or directly from the atmosphere (*Direct Air Capture*, DAC). There are three main technical approaches: post-combustion capture (CO₂ is separated from flue gases after combustion), pre-combustion (the fuel is converted into hydrogen and CO₂ before burning) and oxy-combustion (burning with pure oxygen instead of air, producing an almost pure CO₂ exhaust stream that is easier to separate).

Utilisation — the captured CO₂ is used as a raw material instead of simply being buried: in *enhanced oil recovery* (injected into oil fields to increase their recoverability, historically the most widespread use), in the production of synthetic fuels, cement and plastics, or as an input for greenhouse agriculture.

Storage — CO₂ that is not used is compressed and injected into deep geological formations (depleted oil/gas fields, deep saline aquifers), where it should remain trapped for geological periods.

An important practical limitation is the cost of this mitigation measure: CCUS remains an expensive technology today, not yet scaled up to industrial level — which is why, in investment models (see Chapter 6), the economic comparison often penalises this option relative to simply buying permits, unless the carbon price is high enough to justify the investment.

intensive assets); and **liability risks** (*liability risk*), linked to growing climate litigation against companies and public administrations.

Regulations such as the Sustainable Finance Disclosure Regulation, the EU Taxonomy and the Corporate Sustainability Reporting Directive have made this assessment systematic, channelling capital towards Green Bonds, thematic funds and sustainable infrastructure. In this context, the CO₂ price has itself become a macroeconomic variable: for many European companies the EUA price is now a quantity comparable to oil, natural gas and electricity prices, so much so that a growing number of companies adopt an **Internal Carbon Price (ICP)** — an internal CO₂ price used in investment analysis regardless of the current market price, to assess project profitability under scenarios of progressively rising carbon prices. It is precisely this transformation — from EUAs as a compliance cost to EUAs as a financial variable and, increasingly, as a stand-alone portfolio component — that Chapters 7 and 8 will examine in detail.

4.7. Mitigation, adaptation and geoengineering

The chapter closes by addressing the optimal choice between mitigation, adaptation and, in extreme cases, geoengineering. Studies based on integrated assessment models (*Integrated Assessment Models (IAM)*), such as DICE, MERGE, RICE, TIAM⁵) show that the optimal combination depends crucially on the discount rate: a high rate favours adaptation, which is effective in the short term; a low rate favours mitigation, whose benefits materialise mainly in the long term. In most scenarios, however, mitigation and adaptation turn out to be complements rather than substitutes, and uncertainty about the severity of damage tends to delay both — a dangerous delay in the presence of tipping points, as discussed in Chapter 2.

The two broad families of geoengineering techniques discussed in the original text — removal of CO₂ from the atmosphere (ocean fertilisation, carbon capture and storage) and solar radiation management (injection of sulphur aerosols into the stratosphere, marine cloud brightening) — remain the subject of debate. While the first family, in particular *Direct Air Capture*, has seen falling costs and growing industrial interest over the past decade, the second continues to entail largely unknown risks and side effects (alteration of the hydrological cycle, ozone depletion, inability to counter ocean acidification), which is why the most recent literature still recommends that it play, at most, a marginal role complementary to mitigation and adaptation.

⁵ For more on these models, see the [website](#) of the *IAM Consortium* or the UNFCCC [page](#) on the subject.

5. Economic growth and the environment

In this chapter we address a fundamental question: is the climate crisis an accident along the way of an otherwise sound economic system, or the symptom of a structural flaw in the growth model itself? To answer it, we review the major theories of economic growth, enriching them with the environmental dimension, and complement this theoretical analysis with the most recent empirical evidence on the relationship between growth and emissions in the European Union.

5.1. Growth theories and the role of natural resources

Economic history shows that for millennia global living standards remained essentially stagnant; only after the Industrial Revolution do we observe sustained and continuous growth, first in Europe and its Western “offshoots”, then — far more unevenly — in the rest of the world. Four major paradigms of growth theory can be identified: the neoclassical **Solow-Swan** model, in which long-run growth comes to a halt in the absence of exogenous technological progress because of diminishing returns to capital; the **AK** model, in which capital accumulation generates endogenous growth; **Romer’s** product-variety model, in which growth stems from the continuous invention of new intermediate goods through research and development; and the **Schumpeterian** model, in which growth stems from quality innovations that continually displace existing products (“creative destruction”).

None of these classic models explicitly considers the role of the environment. A simplified AK-type model shows what happens when production also depends on an exhaustible natural resource (such as fossil fuels): if the extraction rate remains positive and constant, the resource stock is necessarily exhausted in finite time, and with it the economy’s productive capacity. Only an extraction rate that declines over time — or the progressive substitution of the natural resource with other forms of capital, in particular human capital and technological innovation — can avoid this long-run collapse.

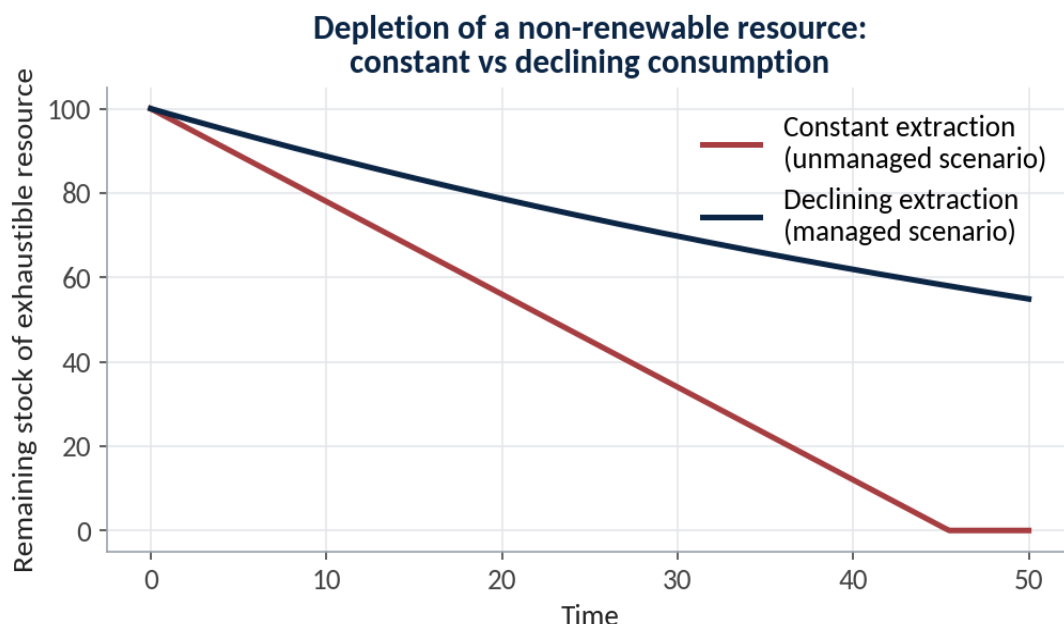


Figure 5. The stock of an exhaustible resource falls to zero in finite time if the extraction rate remains constant; a declining extraction path slows but does not prevent depletion, unless there is substitutive technological innovation.

With a renewable resource (water, fisheries, forests), on the other hand, positive and sustainable growth over time is possible, provided that the harvesting rate does not exceed the natural regeneration rate of the stock: beyond this threshold, even a renewable resource is depleted.

5.2. Technological innovation, carbon budget and weak/strong sustainability

Extending the model with a research and development sector, in which a share of the labour force produces innovations that raise the economy's overall productivity, the main result is that long-run economic growth remains possible even with exhaustible natural resources, provided that the technological progress generated by research grows faster than the rate at which extraction of the natural resource declines — a result known as **weak sustainability**: it does not matter in what form capital (natural, physical or human) is passed on to future generations, as long as overall productive capacity is maintained. This notion is contrasted with **strong sustainability**, according to which certain components of critical natural capital — biodiversity, the ozone layer, climate stability — cannot be substituted by other forms of capital and must be preserved in their own right.

A second model explicitly introduces the concept of the **carbon budget**, already discussed in more operational terms in Chapter 2: the maximum quantity of greenhouse gases that can still be released into the atmosphere without causing irreversible alteration of the climate system. The model contrasts a “dirty” production technology (which consumes the carbon budget) with a “clean” one (which does not draw on it): if the productivity of the dirty technology exceeds that of the clean technology, the whole economy will tend to specialise in the former, with the risk of exhausting the carbon budget and causing a productive collapse. A tax on dirty production, calibrated so as to make the net productivity of the clean technology higher than that of the dirty one, can redirect the whole economy towards clean production — a result that reinforces, from a long-run growth perspective, the logic of the carbon pricing instruments already discussed in Chapter 4. Formally, the carbon intensity of the economy can be decomposed into the product of GDP growth, the energy intensity of GDP and the carbon intensity of energy: by acting on each of these three factors — less energy per unit of GDP, and less carbon-intensive energy — total emissions can fall even with economic growth.

5.3. Decoupling in the European Union: the evidence 1990-2024

From a mainly theoretical discussion of the relationship between growth and emissions, we now turn to an empirical case of particular relevance: the experience of the European Union. Between 1990 and 2024, EU GDP grew by more than **70%**, while net domestic greenhouse gas emissions fell by around **40%**, reaching in 2024 their lowest level since the 1990 base year. The emission intensity of the European economy fell from around 521 grams of CO₂ equivalent per euro of GDP in 1990 to around 184 grams in 2024.

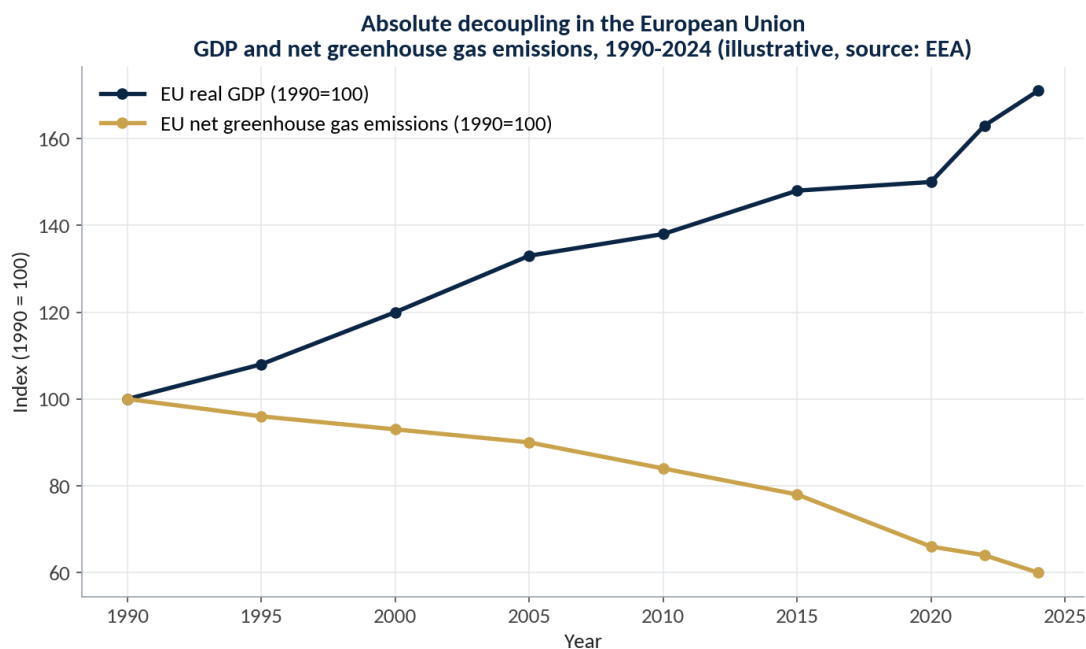


Figure 6. Absolute decoupling in the European Union: indexed trend (1990=100) of real GDP and net greenhouse gas emissions, 1990-2024 (illustrative representation, source: European Environment Agency).

This phenomenon, known as **absolute decoupling**, is crucial for European climate policy: reducing emissions does not necessarily require a reduction in Gross Domestic Product, provided that growth is accompanied by a progressive reduction in the energy and carbon intensity of the economy. The reduction has been driven above all by the growth of renewable energy, the reduced use of coal, greater energy efficiency, the structural transformation of the economy and, not least, the introduction and progressive strengthening of the **EU ETS**, whose principle is simple: emitting CO₂ is no longer economically free, and the EUA price creates a direct incentive to reduce emissions, improve efficiency, switch fuels and invest in clean technologies.

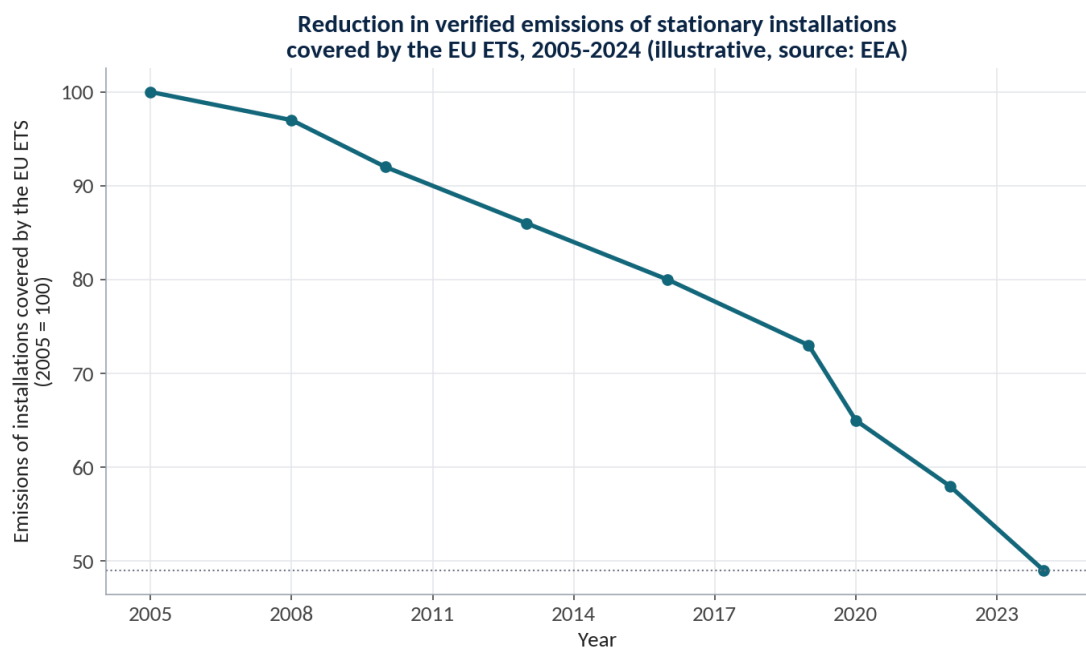


Figure 7. Reduction in verified emissions from stationary installations covered by the EU ETS, 2005-2024 (illustrative representation, source: European Environment Agency): -51% over twenty years.

The European Environment Agency estimates that, from 2005 to 2024, emissions from stationary installations covered by the EU ETS fell by around **51%**, with a particularly significant reduction in the power sector, where the switch from coal to gas and renewables played an important role. The EU ETS is not, however, the only cause of the reduction: technological change, renewables policies, energy efficiency and structural changes in the economy all contributed to the result at the same time.

5.4. Beyond growth: the limits of GDP and the green growth paradox

As in the original edition, the chapter closes with a critical reflection on GDP as a measure of well-being: GDP counts only the monetary value of market transactions, treats all monetary values as equivalent, and ignores both non-market activities and environmental and social damage. Alternative indicators, such as the **Human Development Index (HDI)** or the concept of **material throughput** — the total quantity of matter and energy passing through the economic cycle, from extraction to disposal — attempt to correct these limitations. An often overlooked point, which is particularly relevant today, is that the energy transition does not eliminate the problem of natural resource scarcity: it changes it, shifting it from an economy based on fossil fuels to one in which electricity, critical materials, minerals and infrastructure become more important — hence the growing attention, already mentioned in Chapter 4, to the European Critical Raw Materials Act.

It is also useful to distinguish between **relative decoupling** (CO₂ per unit of GDP falls, but absolute emissions can still rise if GDP grows faster) and **absolute decoupling** (emissions fall in absolute terms even as GDP grows) — the latter is the only one that guarantees an actual reduction in emissions, and it is precisely what has been observed in the European experience of 1990-2024 discussed above. The question remains open, however, raised by economists such as Daly, Jackson and Victor, as to whether continuing this process at a pace compatible with climate neutrality by 2050 also requires a more radical rethinking of growth paradigms for high-income economies, while growth would remain a legitimate priority for low-income economies. A box in the original edition, devoted to financial speculation on food prices in 2007-2012, remains a useful reminder that commodity markets — including, as we will see in the next two chapters, emission allowances — are never entirely immune to financial dynamics that go beyond physical fundamentals alone.

6. The finance of environmental investments: the real options approach

This is the central and by far the most important chapter: real options theory applied to investment decisions is, in our view, the most appropriate tool for appraising this type of investment. Leaving aside the macroeconomic perspective of the previous chapters, we focus here on the individual regulated firm, which must decide whether and when to invest in less polluting technologies, or simply buy emission allowances on the market. The traditional tool for these decisions — Net Present Value (NPV) — is compared with the real options approach, which is better suited to capturing the flexibility inherent in every investment decision.

6.1. The limits of Net Present Value

Every investment project has six characteristics that a decision criterion should be able to capture:

- i. uncertainty about future prices,
- ii. the degree of (ir)reversibility of the decision,
- iii. the possibility of postponing it,
- iv. implementation lags,
- v. the possibility of proceeding in successive stages, and
- vi. the presence or absence of competitors (which may prompt the firm to bring the decision forward so as not to lose a *first-mover* advantage, or allow it to take more time under monopoly conditions).

The NPV criterion simply calculates the discounted sum of the expected positive and negative cash flows generated by a project, and recommends going ahead if the result is positive. Its main limitation is that it is a static criterion: it implicitly assumes that the investment must be made now or never, ignoring the value of waiting. In reality, postponing a decision makes it possible to gather new information and to avoid, if conditions deteriorate, a loss that would have been irreversible. NPV also requires a reliable estimate of future cash flows and the discount rate, which is often unrealistic in a context of high uncertainty such as environmental regulation.

6.2. An investment is an option

The central insight of the chapter is that an investment opportunity shares the structure of a financial option: it gives the right, but not the obligation, to make an outlay (the exercise price, equivalent to the cost of the investment) in exchange for an underlying asset (the present value of the future cash flows generated by the project), within (American option) or at (European option) a certain expiry date.

A numerical example clarifies the point: a utility is evaluating the construction of a gas-fired plant, with an investment cost of EUR 500 million and expected cash flows of EUR 400 million. The NPV is negative (-100 million) and the traditional criterion would suggest not investing. But the project still has value as an option: if expected cash flows were to rise in the future — for example to 600 million, bringing the NPV to +100 million — the firm could decide to invest then. The crucial point is that, at the moment the option is exercised (the investment is made), the opportunity to wait disappears for ever: the correct decision is therefore not to compare NPV with zero, but to compare it with the value of the option to wait. If the latter is higher than the current NPV, it pays to wait even when the NPV is already positive.

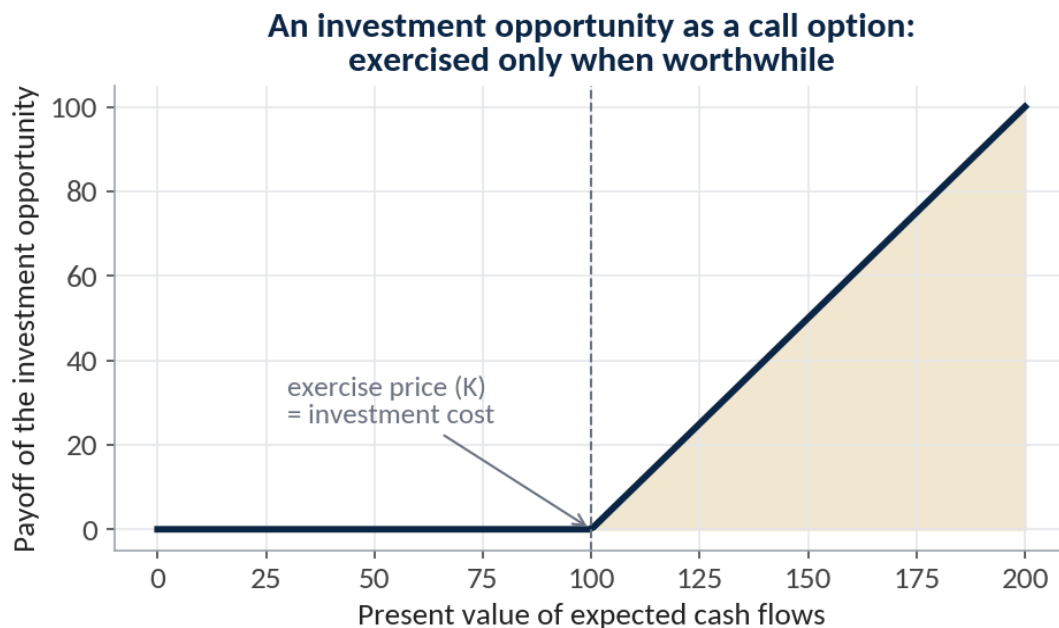


Figure 8. The payoff profile of an investment opportunity is identical to that of a call option: it has value even when the project, if carried out today, would have a negative NPV, because the future scenario could improve.

A second example, applied to a carbon capture and storage (CCS) project whose value depends on the uncertain future price of emission reduction certificates, shows in practice how NPV may recommend immediate investment, whereas an analysis that takes into account the possibility of waiting a year to observe how the price evolves — and therefore of investing only in the favourable scenario and avoiding the unfavourable one — leads to a higher project value and a recommendation to wait.

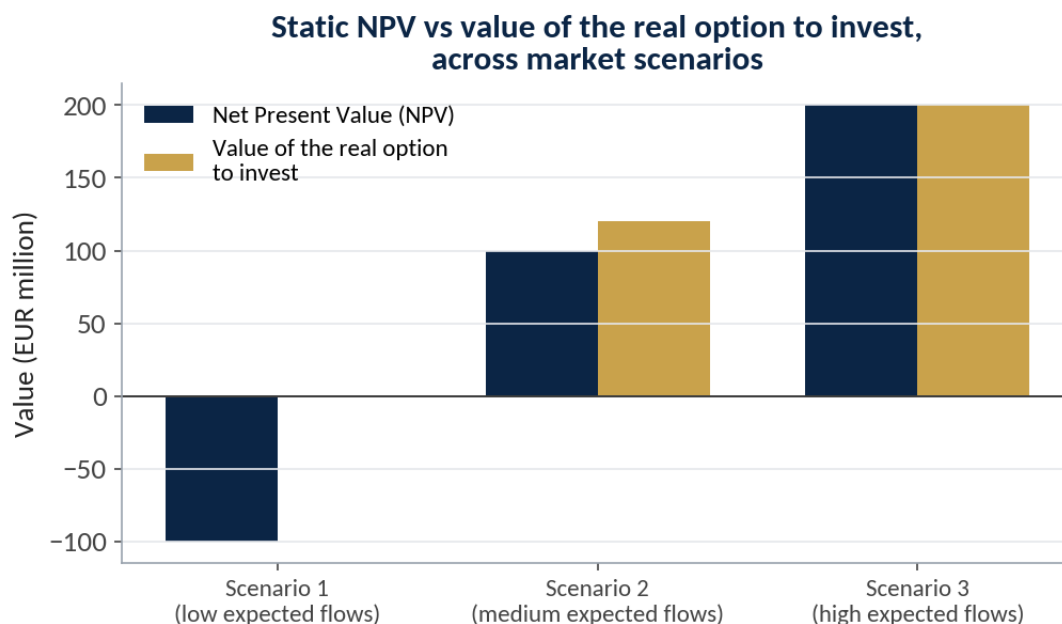


Figure 9. As the market scenario changes, the value of the real option to invest is always greater than or equal to the static NPV: the difference is the value of waiting (or time value of the option).

However, the chapter also shows the opposite case: when the decisions of several competing firms interact — for example in the EU ETS market, where the price of permits depends on the aggregate purchase or investment decisions of all regulated firms — the real options approach may recommend investing earlier, not later, than the

static NPV criterion. If many firms choose to buy permits rather than invest in clean technology, demand for permits rises, their price rises, and at some point it becomes more advantageous to have invested early in clean technology and to sell surplus permits, rather than continuing to buy them at rising prices.

6.3. Valuation tools: the binomial model and the Black-Scholes formula

To translate this insight into a number, we turn to the two classic tools of financial option pricing theory. The binomial model represents the future value of an underlying asset as a sequence of discrete steps, in each of which the value can rise or fall by a fixed factor, with probabilities set so as to rule out any arbitrage opportunity. Repeating this procedure over several periods produces a “tree” of possible paths, and today’s option value is obtained simply by calculating the expected value, discounted at the risk-free rate, of the option payoff in each final scenario, working backwards through the tree (*backward induction*) from the future to the present.

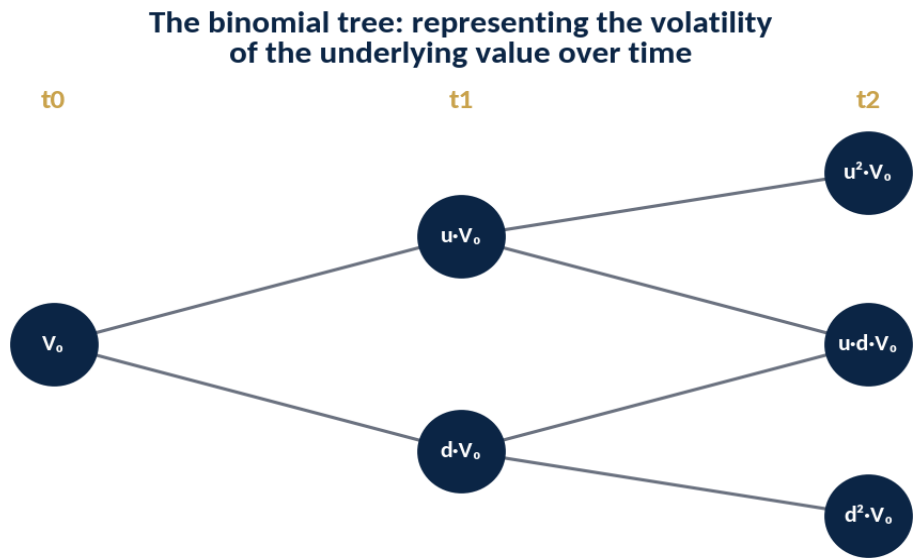


Figure 10. The binomial tree breaks down uncertainty about the future value of the underlying asset (for example a project’s expected cash flows, or the price of an emission allowance) into a sequence of up or down steps.

As the number of time steps tends to infinity (and their length tends to zero), the binomial model converges to the famous Black and Scholes (1973) formula, which provides a closed-form analytical solution for the value of a European option as a function of just five observable or estimable parameters: the current value of the underlying asset, the exercise price, the time to expiry, the risk-free rate and the volatility of the underlying asset’s returns. Of these five parameters, only volatility is not directly observable on the market: it can be estimated from the historical series of past returns (historical volatility), or inferred from the current market price of an option already traded (implied volatility). The assumption of constant volatility over time, which underpins the Black-Scholes formula, is however often violated empirically — as shown, for example, by the volatility “clusters” historically observed in emission credit prices, a topic taken up with more modern tools in Chapter 8.

The following table summarises the analogy — central to the whole chapter — between the parameters of a financial option and those of a real investment opportunity.

Financial option parameter	Real investment equivalent
Price of the underlying share	Present value of the project's expected future cash flows
Exercise price	Present value of the investment cost
Time to expiry	Duration of the investment opportunity (as long as it remains available)
Volatility	Volatility of the return on the project's value
Dividends	Cost of keeping the opportunity alive (e.g. risk that a competitor moves first)
Risk-free rate	Risk-adjusted weighted average cost of capital (WACC)

Table 5. Comparison between financial and real options.

There is a parallel among the six parameters shown in Table 5 that deserves closer examination and a fuller explanation, namely:

Dividends	Cost of keeping the opportunity alive (e.g. risk that a competitor moves first)
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First of all, let us understand why a dividend reduces the value of a financial call. Imagine holding a call option on a share (the right, but not the obligation, to buy it at a fixed price in the future). As long as we hold the option — that is, as long as we do not exercise it by buying the share — we do not receive the dividends the share pays in the meantime: those dividends go only to whoever physically owns the share, not to whoever owns only the right to buy it.

Every dividend paid while waiting is therefore a piece of value that “escapes” from the share and that the holder of the (not yet exercised) option does not capture. The higher the expected dividends, the more costly it is to wait — because every day the option is not exercised, a piece of value is lost that would instead have been collected had the share been bought straight away. This is why, in option pricing models, a higher dividend reduces the value of the call and encourages early exercise (in American options).

Now let us replace “share” with “investment opportunity” (for example building a renewable energy plant). The option here is “waiting to invest”. The question becomes: what is lost for every day the investment is postponed, i.e. how much is the forgone gain compared with having invested immediately?

There are two main types of “value leakage” equivalent to the dividend:

- 1) The cash flows the plant would generate if it were already operational. If the project, once built, produces a positive cash flow every year, then every year of postponed construction is a year of cash flow not collected — exactly like the dividend that is not collected until the call is exercised.
- 2) The risk that a competitor anticipates our moves. This is the specific case cited in the table: if the market is competitive and a competitor can seize the same opportunity (for example, being the first to occupy a technological niche, secure a favourable site or win market share), then waiting carries the risk of losing

the opportunity entirely, not just postponing its benefits. It is as if the “dividend” in this case were not a small, steady flow, but a risk of total loss of the underlying if someone else “collected” it in our place.

This parallel serves to explain a practical point: the higher the “dividend” (flows lost while waiting, or the risk of being pre-empted), the less it pays to wait. A firm operating in a highly competitive market — where the risk of being pre-empted by a competitor is high — has a stronger incentive to invest immediately even with a modest NPV, because the cost of waiting (the “implicit dividend”) is high. Conversely, a firm in a monopoly position, with no competitors threatening to move first, has an almost zero “dividend” and can afford to wait a long time gathering information, because the value of the opportunity does not deteriorate in the meantime.

An American option — exercisable at any time before expiry, not only at expiry as in the European case — introduces a further element: at each node of the tree, the value of immediate exercise must be compared with the expected value of continuing to wait. As long as this “time value” remains positive, it pays to wait; when it falls to zero, it pays to exercise immediately. This logic is particularly relevant for put options, which in the environmental context represent divestment decisions (for example the resale of surplus permits). In the environmental context, a natural put is the following: a firm holding surplus emission allowances has, in a sense, the right — but not the obligation — to resell them on the market when the price is favourable. This is exactly the structure of a put: the firm can dispose of the asset (the permits) when it is advantageous to do so, without being obliged to if the market price is not high enough.

The reason why this “comparison at every node” logic is particularly relevant for a put of this kind lies in the very nature of the decision: the choice to resell permits does not arise as a one-off event tied to a fixed date, but as a decision to be continually reassessed over time as the permit price evolves on the market. If the current price is already high, immediate sale may be the optimal choice (the time value has fallen to zero); if, on the other hand, there remains a significant probability of further increases, it is preferable to hold on to the permits and wait — following a logic that mirrors that of the call.

In short, divestment decisions in the permit market are not one-off events tied to a predetermined expiry, but decisions subject to continual reassessment over time — a flexibility that, unlike the European model, the American model is specifically designed to represent.

6.4. Applications to compliance with environmental regulation

The final part of the chapter systematically applies these tools to a sequence of increasingly realistic cases, in which a regulated firm must decide how many permits to buy or sell (and, in some cases, whether to change its production technology) to meet its compliance obligation at the end of the period, avoiding the penalty for emissions not covered by permits.

- A one-period model, with no possibility of postponing the decision, shows that the firm optimises the quantity of permits to buy by balancing the risk of having to pay the penalty (if emissions exceed expectations) against the risk of having bought surplus permits, which have no redemption value at expiry. When the penalty is much higher than the current permit price (as is typically the case), the optimal strategy tends to cover the worst-case scenario, even at the cost of being left with a surplus of permits in the favourable scenario.
- A two-period model introduces the possibility of trading permits midway as well, making it possible to distinguish in practice between the real options approach and static NPV. The optimal strategy under real options involves buying more permits than NPV would suggest, precisely because the surplus bought today

is the “seed” of a future resale option (an implicit put option⁶) that has an economic value of its own, ignored by the static criterion.

- A model with the possibility of changing technology shows that the optimal choice between continuing to buy permits and incurring the (fixed) cost of adopting a less polluting technology depends on the comparison between the cost of technological conversion and the expected benefit in terms of emission reductions: if the achievable reduction is too small, or the conversion cost too high, it pays to stay with the existing technology and cover requirements by buying permits.
- Finally, a model with two firms in strategic interaction endogenises the permit price itself, which emerges from the meeting of the two firms’ demand and supply, each with partial information on the other’s emissions. The equilibrium price is the one at which net demand for and supply of permits between the two firms is zero.

The common thread throughout this section is that the real options approach, while requiring more sophisticated quantitative tools than simple NPV, systematically captures a value — that of the flexibility to wait, to change strategy, to divest — which NPV, by construction, cannot see. In the specific context of carbon markets, where regulatory uncertainty (extensions, reforms, the end of commitment periods) adds to market uncertainty, this value of flexibility is often significant and far from negligible in planning industrial investment — a principle that, as the following chapters will show, still holds today now that European Union Allowances are traded on financial markets far more liquid and sophisticated than they were just ten years ago.

⁶ See section 6.3.

7. Financial markets for emission allowances

The European emission allowance market has evolved from a simple administrative mechanism for meeting environmental obligations into a market characterised by high liquidity, sophisticated derivatives, broad participation by financial operators and trading infrastructure comparable to that of the main energy commodities. Understanding this infrastructure is an essential prerequisite for the even more specialised analysis in Chapter 8, devoted to European Union Allowances (EUAs) as an asset class.

7.1. From administration to finance: the infrastructure of the EU ETS

The central element of the EU ETS is the **European Union Allowance (EUA)**: the right to emit one tonne of carbon dioxide equivalent (tCO₂e). From an economic standpoint, the EUA has peculiar characteristics: it is neither a physical commodity, nor a share, nor a bond, nor a currency, but a **transferable emission permit**, created by European legislation and tradable on the market. Its economic value derives exclusively from the scarcity introduced by the legislator through the annual emissions cap, and arises from the interaction between European regulation, firms' compliance demand, market participants' expectations and the fundamentals of energy markets — a hybrid nature that will be analysed in detail in Chapter 8.

Several institutions are involved in the functioning of the market: the **European Commission** sets the general regulatory framework (setting the cap, managing the Market Stability Reserve, coordinating with Member States); the **Member States** retain operational responsibilities such as permitting installations and verifying emissions; the **national competent authorities** ensure the proper operational functioning of the system in their respective territories.

7.2. The life cycle of an EUA and the Union Registry

Each emission allowance follows a precise life cycle. The European Commission determines each year the total number of allowances available (**issuance**); allowances are distributed through public auctions, free allocation or European funds dedicated to innovation and modernisation (**allocation**); once allocated, they can be freely transferred between participants, both on regulated markets and through bilateral OTC contracts (**trading**); they are held in the **Union Registry**, the official electronic registry of the European Union, which plays a role similar to that of a central securities depository; by the annual deadline, every company subject to the EU ETS must *surrender* a number of allowances equal to its verified emissions (**compliance**); finally, the allowances used are permanently **cancelled** from the system. The existence of the Union Registry eliminates the risk of double counting of allowances and is one of the essential elements of the market's environmental integrity.

7.3. Primary market, secondary market and trading venues

EUAs enter the market through the **primary market**: auctions, now the main allocation mechanism, organised by the **European Energy Exchange (EEX)** on behalf of the Member States and the Commission; free allocation, reserved for the sectors most exposed to international competition and set to decline progressively as CBAM comes into force; and European funds (*Innovation Fund, Modernisation Fund*), whose allowances are monetised through dedicated auctions.

After initial allocation, EUAs are freely traded on the **secondary market**, quantitatively the most significant component of the entire system, through regulated markets, multilateral trading facilities and OTC contracts. The main secondary market is **ICE Futures Europe**, which hosts almost all trading in EUA derivatives and makes it the international benchmark for the CO₂ price; EEX, in addition to its role in primary auctions, also offers spot trading.

An efficient secondary market enables participants to hedge price risk, optimise compliance management and support efficient price formation.

7.4. Derivatives: futures, options, calendar spreads, OTC and Exchange Traded Products

EUA **futures**, traded mainly on ICE Futures Europe, are standardised contracts cleared through a central counterparty (CCP), available with monthly, quarterly and annual maturities. **December Futures**, expiring in December, are the market’s main reference point and are widely used by utilities, industrial companies, banks and institutional investors; the term structure of maturities (*forward curve*) also provides important indications of the market’s expectations regarding the future evolution of the CO₂ price.

Alongside futures, a market has developed in **options**, which give the buyer the right, but not the obligation, to buy (*call*) or sell (*put*) EUA futures at a predetermined price within a given expiry; puts are particularly useful as a hedge against a fall in allowance prices. An instrument widely used by professional operators is the **calendar spread**: buying a futures contract with one maturity and simultaneously selling a contract with a different maturity, which makes it possible to trade directly on changes in the term structure of prices (useful for arbitrage and hedge optimisation).

Alongside regulated markets there is an important **Over-The-Counter (OTC)** segment, in which contractual terms (forwards, swaps, customised options, allowance lending) are negotiated directly between the parties, offering greater flexibility but requiring more elaborate management of counterparty risk; a growing share of these transactions is now subject to the clearing and reporting obligations of the European EMIR regulation. As market liquidity has grown, instruments typical of traditional finance have also appeared, such as **repo** and **securities lending** transactions on allowances, and listed products — **Exchange Traded Commodities (ETCs)**, **Exchange Traded Notes (ETNs)** and, more generally, **Exchange Traded Products (ETPs)** — that track EUA futures or specific indices, allowing investors to gain exposure to the CO₂ price without directly holding allowances in the Union Registry. The number of pure UCITS ETFs on EUAs, by contrast, remains limited, mainly for regulatory reasons linked to the difficulty of treating EUAs as one of the traditional underlyings eligible for this type of fund.

7.5. Market participants

The EU ETS is today one of the few markets in which participants with profoundly different objectives coexist, a factor that contributes decisively to the liquidity and efficiency of the system.

Category of participant	Main role in the market
Utilities	Purchase of EUAs in proportion to the CO ₂ generated; main users of futures to hedge future costs
Industrial companies (steel, cement, chemicals, refining)	Demand for EUAs linked to European industrial output
Aviation and maritime transport	Compliance for emissions from intra-European flights and, since 2024, shipping
Banks	Intermediation, market making, derivatives structuring, financing, clearing
Commodity trading houses	Arbitrage between EUAs and other energy commodities (gas, electricity, coal)
Hedge funds and asset managers	Directional investment, relative value, spread trading, macro strategies

Category of participant	Main role in the market
Market makers	Continuous bid/ask quotes; narrower spreads and price discovery

Table 6. Main participants in the European ETS.

7.6. Price formation and the compliance cycle

The EUA price derives from the interaction between structural supply-side factors — the level of the cap, its annual reduction, the auction calendar, remaining free allocations and the intervention of the **Market Stability Reserve (MSR)** — and demand-side factors, first and foremost industrial output, electricity demand, weather conditions and the relative prices of natural gas and coal. The MSR, already introduced in Chapter 3, acts as a countercyclical mechanism: when the number of allowances in circulation exceeds certain thresholds, it temporarily withdraws part of them from the market; conversely, in the event of scarcity, it releases part of them, contributing decisively to market stabilisation and price credibility.

Empirical analyses carried out by the European Commission and the European Securities and Markets Authority (ESMA) indicate that, although the participation of financial investors has increased, the EUA price continues to be explained mainly by market fundamentals — the level of the cap, demand for allowances and the marginal abatement cost — rather than by purely speculative dynamics. The presence of financial operators alongside industrial ones in fact helps to increase liquidity, price efficiency and hedging opportunities, although it may amplify short-term volatility in the event of sudden changes in macroeconomic or regulatory expectations.

7.7. Are EUAs a commodity?

One of the most frequently asked questions concerns the economic classification of European Union Allowances. Operationally, EUAs are traded on organised markets in the same way as energy commodities, with a spot market, futures and options; unlike oil, natural gas or metals, however, they are not a physical good intended for consumption or industrial processing, and their value depends to a large extent on regulatory variables and on how climate policy evolves. For these reasons, the most recent economic literature tends to regard them as a **regulated asset class**, with hybrid characteristics placing them halfway between commodity markets and financial instrument markets — a theme that Chapter 8 will develop systematically.

The development of financial instruments on EUAs has transformed the European carbon market into a sophisticated ecosystem in which regulatory compliance, risk management and financial investment needs coexist. The value of EUAs nevertheless continues to depend decisively on the economic and regulatory fundamentals of the EU ETS: to fully understand price behaviour, it is necessary to analyse systematically these fundamental drivers, the quantitative models used by professional operators and the investment strategies adopted by companies and institutional investors — the specific subject of the following chapter.

8. European Union Allowances as an asset class

The underlying message of the corresponding chapter of the original work is as follows: the price of emission allowances is not arbitrary, but precisely reflects the marginal abatement cost or the probability of a permit shortfall at expiry; the empirical and quantitative analysis surrounding it, however, calls for a more in-depth treatment, because over the past decade European Union Allowances (EUAs) have become one of the most significant innovations developed by environmental and financial markets: born in 2005 as an administrative compliance tool, they are now traded by industrial companies, utilities, banks, commodity traders, hedge funds and institutional investors, and for many participants represent a fully-fledged **new asset class**.

8.1. The historical evolution of EUAs (2005-2026)

The evolution of the market can be divided into four phases, which mirror those already described for the EU ETS in Chapter 3. In the **first phase (2005-2007)**, a pilot phase, allowances were mostly free and the market was still illiquid: the lack of operational experience and the overestimation of emissions resulted in a large oversupply that drove the EUA price down to near zero by the end of the period, since permits from that phase could not be banked into the next one⁷. In the **second phase (2008-2012)**, which coincided with the first Kyoto commitment period, the global financial crisis sharply reduced European industrial output, generating a new surplus. The **third phase (2013-2020)** marked the real turning point, with auctioning as the main allocation mechanism, the single European registry, harmonised rules and the introduction of the Market Stability Reserve: the EUA price began to reflect increasingly the regulatory scarcity introduced by the Commission. The **fourth phase (2021-2026)**, under way, has seen the acceleration of the cap reduction, the strengthening of the MSR, the inclusion of maritime transport, the introduction of ETS2 and the gradual replacement of free allocation by CBAM, definitively consolidating the role of EUAs as a financial asset of systemic importance.

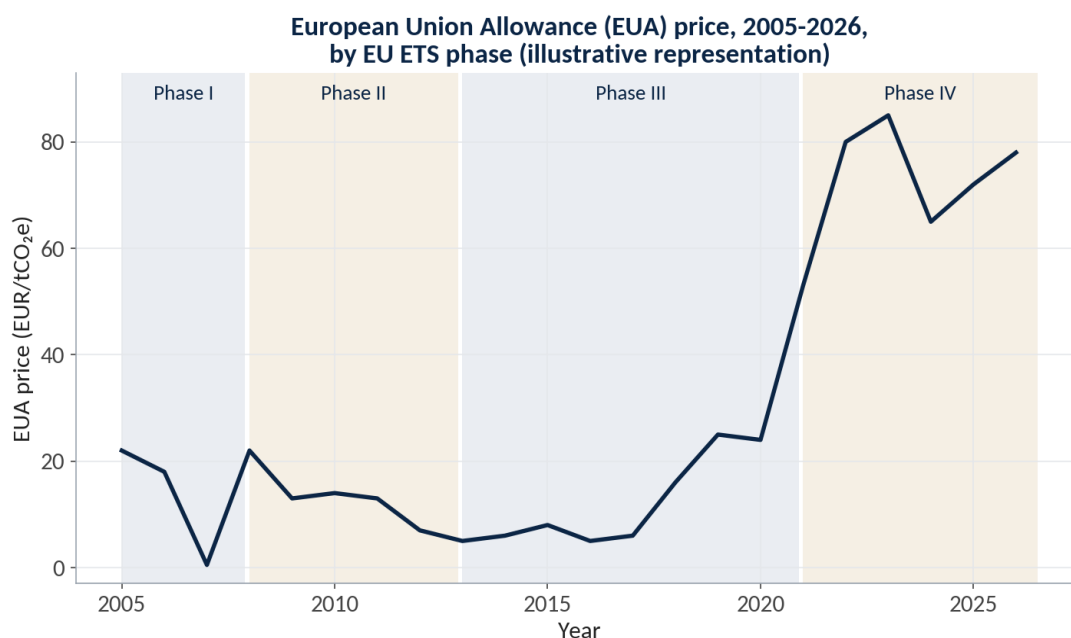


Figure 11. Evolution of the European Union Allowance (EUA) price, 2005-2026, by EU ETS phase (illustrative representation). The collapse of Phase I, the post-financial-crisis surplus of Phase II, the stabilisation of Phase III thanks to the Market Stability Reserve and the strong structural growth of Phase IV are the four distinctive features of the historical series.

⁷ That is, they could be neither banked nor borrowed.

Every year, billions of tonnes of CO₂ equivalent are now traded through primary auctions, the spot market, futures, options and OTC contracts; the notional value of trading far exceeds that of the physical allowance market, and most trading activity is concentrated in futures contracts traded on ICE Futures Europe, the international benchmark for the EUA price.

8.2. Why EUAs are neither a commodity nor a traditional financial instrument

At first sight, emission allowances could be likened to energy commodities: both are traded on organised markets, have futures and options and are influenced by supply and demand. There are, however, profound differences. A traditional commodity has physical substance and can be produced, stored, consumed or transformed; EUAs, by contrast, are intangible goods that exist only within the Union Registry, cannot be “produced” by market participants and derive entirely from a regulatory decision — **regulatory scarcity**: it depends not on geology, agriculture or mining, but on the European Commission’s decisions about the level of the cap.

Nor can EUAs be likened to classic financial assets: they do not represent an equity stake, a debt claim or a currency, and they generate no dividends, coupons, interest or cash flows. Their economic value derives exclusively from the possibility of using them to meet emission obligations or reselling them on the market. A further peculiarity concerns the demand side: whereas for most commodities demand depends solely on production or consumption needs, for EUAs a significant component of demand derives directly from compliance obligations laid down by law — **mandatory demand** — alongside which there is hedging demand, investment demand, arbitrage and market making. The following table provides a concise comparison of EUAs with the main asset classes.

Feature	Equities	Bonds	Commodities	EUAs
Generate cash flows	Yes	Yes	No	No
Physical good	No	No	Yes	No
Supply regulated by the legislator	No	No	No	Yes
Partly mandatory demand	No	No	No	Yes
Futures and options market	Yes	Yes	Yes	Yes
Main driver	Corporate earnings	Interest rates	Physical supply/demand	Cap, energy, regulation

Table 7. Comparison between EUAs and the other main asset classes.

Their uniqueness lies in the simultaneous combination of three elements: regulatory scarcity, mandatory compliance demand and tradability on financial markets. No other asset class has all three characteristics at the same time, which makes EUAs — according to the definition now prevailing in the literature — a **regulated asset class** in their own right.

8.3. The fundamental price drivers: Cap, LRF, MSR and TNAC

As with any asset traded on financial markets, the EUA price is the result of the interaction between supply and demand, but with characteristics profoundly different from those of traditional markets: supply is determined not by the productive capacity of market participants, but by European regulation. The **Cap** is the fundamental factor of the whole system: it sets the maximum number of allowances available in a given year, and plays an economic

role similar to the money supply in a monetary system or to available reserves in a commodity market — the greater the reduction in the Cap, the fewer EUAs will be available and, for a given level of demand, the greater the upward pressure on prices. The **Linear Reduction Factor (LRF)** sets the speed at which the Cap is reduced over time: with the revision of the EU ETS approved as part of the Fit for 55 package, the annual reduction rate was significantly increased compared with previous phases (see Figure 1 in Chapter 3), implying lower future availability of allowances and a stronger price signal.

An indicator constantly monitored by market participants is the **Total Number of Allowances in Circulation (TNAC)**, which measures the total number of allowances available in the system and not yet used for compliance, and is the main indicator of the market's structural surplus: a high TNAC exerts downward pressure on prices, a low TNAC supports them. The decisions of the **Market Stability Reserve** depend directly on the evolution of this indicator, which for this reason is one of the most important variables in EUA price forecasting models. Alongside these structural factors, demand depends on European industrial output (steel, cement, refining, chemicals) and, historically to a predominant extent, on the power generation sector.

8.4. The relationship with energy markets

The EUA price is strongly correlated with energy markets, in particular with the price of **natural gas** (TTF market): when gas becomes particularly expensive, many power producers replace part of their gas-fired generation with coal-fired plants; since coal has a significantly higher emission intensity, allowance consumption increases — a phenomenon known as **fuel switching**, which determines the theoretical “switching price”. The price of **coal** also indirectly influences the market: a fall in it makes power generation from conventional plants more attractive, increasing demand for allowances. Among the indicators most widely used by professional operators are the **Clean Spark Spread** and the **Clean Dark Spread**, which measure the theoretical profitability of power generation from gas-fired and coal-fired plants respectively, including the cost of EUAs: the difference between them provides important indications of the economic viability of fuel switching.

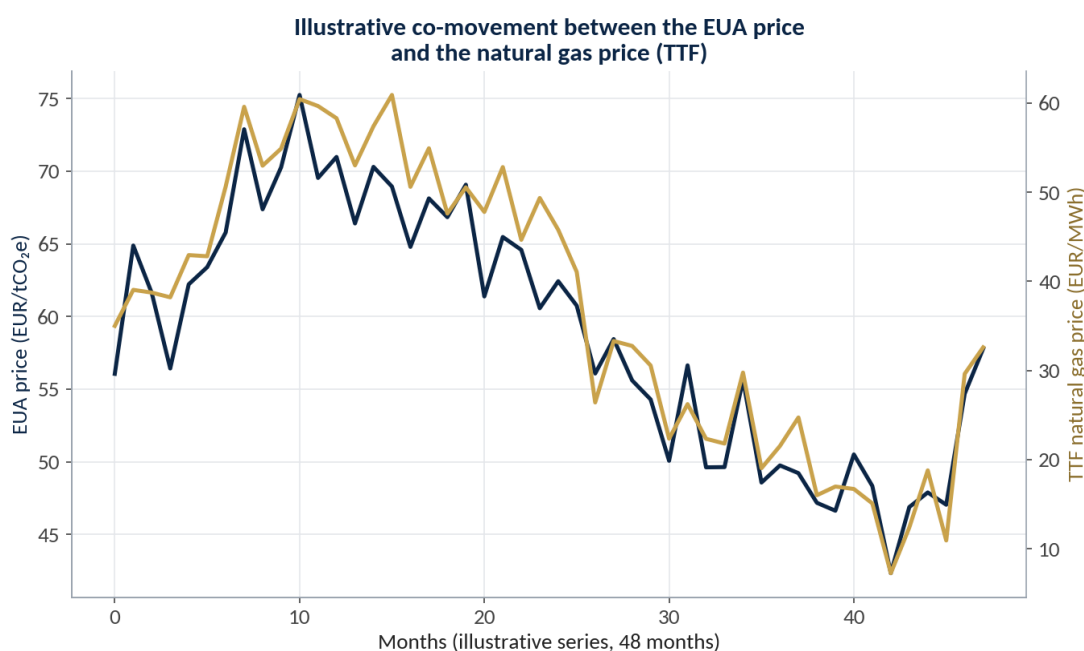


Figure 12. Illustrative co-movement between the EUA price and the natural gas price (TTF): the fuel-switching channel makes the carbon market closely interdependent with energy markets.

Weather conditions (temperature, wind, solar irradiance, hydroelectric availability) and certain macroeconomic variables (European GDP growth, industrial output, business confidence) also continue to play a significant, though generally indirect, role; finally, geopolitical events — such as the European energy crisis of 2021-2023 — can affect the EUA price significantly and rapidly. All these factors can be summarised in a conceptual framework that expresses the EUA price as a function of six groups of variables: **regulatory** variables (Cap, LRF, MSR, CBAM, ETS2), **allowance availability** (TNAC, auctions, free allocation), **compliance demand and industrial activity**, **energy markets** (gas, coal, electricity, renewables), **macroeconomic variables** and **geopolitical factors and expectations**. None of these factors on its own is sufficient to explain the full dynamics of the market: on the main trading desks of utilities, banks and commodity houses, the EUA price is in fact monitored in real time together with the TTF gas forward curve, the API2 coal curve, electricity prices, wind and solar output levels and the EEX auction calendar.

8.5. From fundamental analysis to quantitative models

The theoretical literature on permit price equilibrium, already presented in the original edition, remains the conceptual reference point for understanding why the EUA price is not arbitrary: Montgomery (1972) was the first to show that a system of tradable permits leads to an efficient allocation, with the equilibrium price equal to each firm's marginal abatement cost; Seifert, Uhrig-Homburg and Wagner (2008) and, in more general form, Carmona, Fehr and Hinz (2009) showed that, when uncertainty about future emissions is introduced explicitly, the permit price reflects the probability that cumulative emissions will exceed the assigned cap by expiry, multiplied by the unit penalty; finally, Chesney and Taschini (2012) extended the framework to information asymmetry between competing firms.

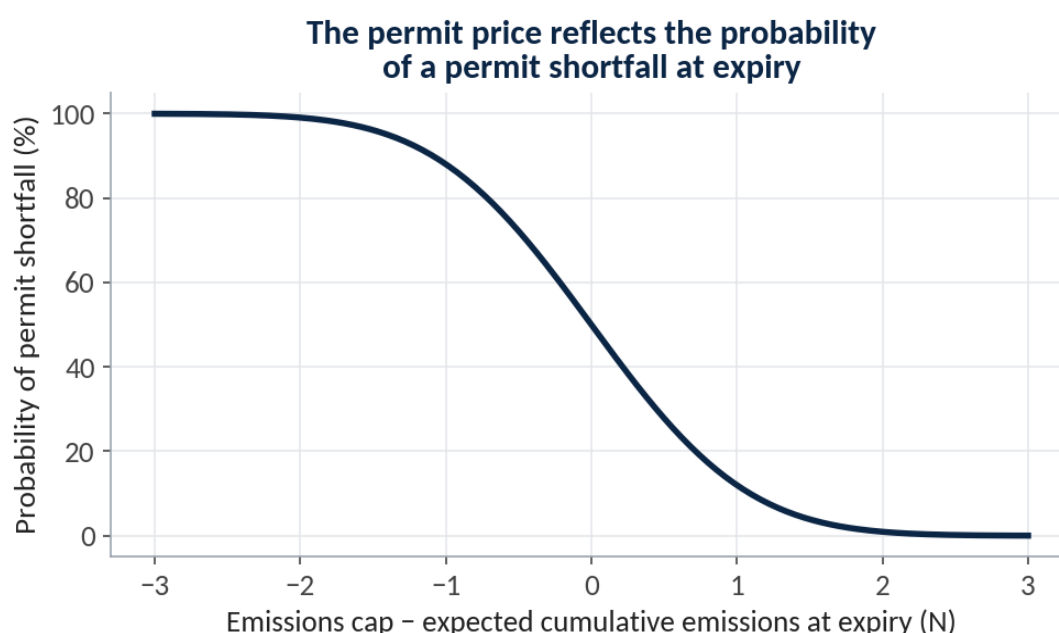


Figure 13. Central result of the equilibrium literature (Seifert et al. 2008; Carmona et al. 2009): the permit price is approximately equal to the penalty multiplied by the probability that cumulative emissions will exceed the emissions cap by expiry.

This theoretical result now coexists with a much broader set of quantitative models, developed by utilities, banks and institutional investors to build probabilistic scenarios rather than point forecasts. **Multivariate regressions** link the EUA price to variables such as the TTF gas price, the coal price, the electricity price, the TNAC and industrial output, providing an initial estimate of the market's sensitivity to individual factors (elasticities); since the relationships between EUAs, gas, coal and electricity are highly dynamic, **VAR (Vector Autoregression)** models are also used, in which all variables are treated as simultaneously endogenous, together with **cointegration**

techniques (Engle-Granger test, Johansen procedure, VECM models) to distinguish long-run relationships from temporary deviations.

Numerous studies show that EUA returns exhibit non-Gaussian distributions, fat tails and time-varying volatility (*volatility clustering*), characteristics that often make the simplest linear models inadequate and justify the use of **ARCH/GARCH** family models to estimate conditional volatility, calculate Value at Risk and set hedging margins. In recent years, **Machine Learning** algorithms (Random Forest, Gradient Boosting, XGBoost) have also become widespread and, where more data are available, deep neural networks (LSTM, Transformer architectures applied to time series), which are particularly effective when the relationships between variables are highly non-linear. Large utilities do not typically produce a single forecast, but build alternative scenarios (base, bullish, bearish) and stress-test their positions, consistent with a probabilistic rather than deterministic approach to risk management.

8.6. Investment strategies and risk management

The strategies adopted by market participants can be grouped into four main categories: **directional investment** (a long or short position depending on expectations for the future CO₂ price); **hedging** (use of futures and options to stabilise the cost of compliance, typical of utilities and industrial companies); **relative value**, based on the relationships between EUAs, natural gas, coal and electricity, including trades based on the Clean Spark Spread and Clean Dark Spread; and **quantitative trading**, which systematically incorporates energy prices, weather forecasts, macroeconomic data and futures curves.

From a portfolio construction standpoint, EUAs offer diversification (their dynamics are driven by factors different from those of equities, bonds, real estate or currencies), direct exposure to European climate policy and the energy transition, and — through the progressive reduction of the cap — potential for structural growth over the long term. The investment does, however, involve specific risk factors: **regulatory risk** (the most significant: changes to the Cap, the LRF or the functioning of the MSR can significantly affect the price), **energy risk**, **macroeconomic risk**, **liquidity risk** on some less-traded instruments, **political risk** linked to developments in the geopolitical context, and **volatility risk** historically higher than that of many traditional asset classes, which calls for careful management of leverage. In all cases, risk management plays a central role, through exposure limits, scenario analysis, Value at Risk, stress tests and liquidity control.

8.7. Outlook to 2030, 2040 and 2050

By **2030** the European carbon market will be affected by a further reduction in the cap, the full implementation of the Fit for 55 package, the progressive phase-out of free allocation in the sectors covered by CBAM, the consolidation of the inclusion of maritime transport and the operational launch of ETS2 for buildings and road transport. Looking ahead to **2040**, greater integration between the various European ETSs, possible extension to other economic sectors, further development of derivatives markets and growing sophistication of quantitative models are expected, while increasing renewable generation and the electrification of the economy could progressively change the structure of demand for allowances.

The European goal of climate neutrality by **2050** raises fundamental questions about the very future of EUAs, for which the literature identifies three alternative scenarios: a first scenario in which EUAs remain the main mechanism for allocating the cost of CO₂; a second, of a scaled-down market, in which the drastic reduction in emissions reduces the overall volume of allowances traded; and a third, of progressive integration of the EU ETS with other carbon pricing systems towards a more global carbon market, for which — as discussed in Chapter 3 — Article 6 of the Paris Agreement provides an initial framework. Which of these scenarios prevails will depend on

political decisions, technological development and the effectiveness of European and global decarbonisation strategies.

After more than twenty years of operation, the experience of the EU ETS shows that carbon pricing can change economic behaviour in a lasting way, that regulatory predictability is essential to encourage investment, that automatic mechanisms such as the Market Stability Reserve help to reduce structural imbalances, and that the integration of climate policy, industrial policy and financial markets is one of the main factors behind the success of the European system — which remains, to this day, the international reference for the design of new emissions trading systems.

8.8. In focus: from the Clean Dark/Spark Spread to the switching price

This section is intended for readers who wish to explore in greater depth the determinants of EUA supply and demand. It is deliberately more technical and brings together, in a single synthesis, a group of closely related concepts that (partly) explain the short-term dynamics of the EU ETS allowance price: the Clean Dark Spread and the Clean Spark Spread, the two fuel price indices (API#2 for coal and TTF for gas), the theoretical switching price (see Equation 1), and the structural role of the TNAC in explaining the gap between this theoretical price and the price actually observed on the market.

8.8.1. From the profit margin of the two technologies to the indifference price

The Clean Dark Spread and the Clean Spark Spread measure the profit margin of a coal-fired and a gas-fired power plant respectively: the selling price of electricity minus the cost of the fuel needed to produce it, also net of the cost of the emission allowances required to cover the CO₂ released. At any given moment, the operator of a generation fleet prefers to run the technology with the higher spread.

In Focus: Dark Spread and Spark Spread

These two concepts are closely linked to the mechanism of **fuel switching**: in practice, they are the tool used to measure, concretely, how worthwhile it is to switch from coal to gas (or vice versa) in a power plant.

What a “spread” means in this context

A spread, in this case, is simply the **profit margin** a power generator earns by selling the electricity it produces, net of the cost of the fuel used to produce it. It is the difference between revenue (the price of electricity) and the main variable cost (fuel).

Dark Spread and Spark Spread: the only difference is the fuel

- The **Dark Spread** is the margin of a **coal-fired** plant: the price of electricity minus the cost of the coal needed to produce it (taking into account the plant’s conversion efficiency — how much electricity is obtained per unit of coal burned).
- The **Spark Spread** is the equivalent margin for a **natural gas-fired** plant: the price of electricity minus the cost of the gas needed, again adjusted for the plant’s efficiency.

The names come from the type of combustion: “dark” for coal (a “dark”, traditional source), “spark” for gas (the spark that ignites the turbine).

Why “clean”

The adjective **clean** indicates that the **cost of the emission allowances** needed to cover the CO2 released by that generation is also deducted from the spread. Therefore:

- **Clean Dark Spread** = price of electricity – cost of coal – cost of emission allowances (for coal’s higher emissions)
- **Clean Spark Spread** = price of electricity – cost of gas – cost of emission allowances (for gas’s lower emissions)

The crucial point is that coal emits more CO2 per unit of energy produced than gas, so the cost of allowances weighs much more heavily on the dark spread than on the spark spread. That is why the “clean” version is needed: without taking the cost of allowances into account, a comparison between the two sources would be incomplete and misleading in a system such as the EU ETS, where every tonne of CO2 emitted has an explicit cost.

The link with the “switching price”

This is exactly the mechanism behind the concept of the **switching price**: the operator of a generation fleet compares the clean dark spread with the clean spark spread, and chooses to run the source that offers the higher margin at that moment.

The switching price is, in essence, **the emission allowance price at which the two clean spreads are equal** — the point of indifference between the two sources. Above that price, the additional cost of allowances penalises coal enough to make gas more attractive (clean spark spread > clean dark spread), and generation shifts towards gas, reducing the power system’s aggregate emissions. Below that price, coal remains the cheaper choice even after allowances.

This is why the switching price, calculated from these two spreads, is used as a **proxy for the short-to-medium-term marginal abatement cost**: it represents, in concrete terms, how much emitting a tonne of CO2 must cost before it becomes economically worthwhile for the power system to reduce its emissions by shifting towards a cleaner source — the same concept of marginal abatement cost we saw in the Weitzman charts, shown here, however, through a market mechanism observable in real time rather than as a theoretical curve.

Equation 1 below formalises this choice by directly calculating the CO2 price at which the two spreads are equal — the so-called switching price, denoted by E_t .

$$E_t = \frac{h_g \cdot G_t - h_c \cdot C_t}{e_c - e_g}$$

Equation 1. — the CO2 price (E_t) that makes producing with gas or coal equally attractive.

Each symbol in the formula has a precise meaning that can be observed on the market:

- E_t : the theoretical switching price at time t , expressed in euros per tonne of CO2: it is the allowance price that makes producing with coal or gas equivalent in terms of profit margin.
- G_t and C_t : the market prices at time t of natural gas and coal respectively, quoted on their respective benchmark indices (NBP for gas and API#2 for coal).

- h_g and h_c : the *heat rates* of gas and coal: the quantity of fuel (in energy terms) needed to produce one unit of electricity. They depend on the conversion efficiency of each technology — a modern combined-cycle gas plant converts fuel into electricity more efficiently than a conventional coal-fired plant, and therefore has a lower heat rate.
- e_c and e_g : the emission factors of coal and gas: the tonnes of CO₂ released per unit of energy by each fuel. Coal has a higher emission factor than gas, which is precisely why a sufficiently high carbon price makes switching from coal to gas worthwhile.

In the numerator, the difference $h_g \cdot G_t - h_c \cdot C_t$ represents the gap between the fuel cost per MWh of electricity produced with gas and with coal. In the denominator, $e_c - e_g$ represents the additional tonnes of CO₂ emitted by coal compared with gas, again per MWh of electricity produced. The ratio between the two terms is therefore the allowance price needed, per tonne of CO₂ saved, to close exactly the fuel cost gap — in other words, the CO₂ price that eliminates the relative advantage of one technology over the other.

In Focus: h_g, h_c, e_g, e_c

Where can these parameters be found? These four parameters come from different sources depending on whether you are looking for “standard” industry values or plant-specific data.

Emission factors (e_c, e_g)

They are the most standardised, because they derive from the chemical composition of the fuel, not from the plant:

- **IPCC Guidelines for National Greenhouse Gas Inventories** (2006, updated in 2019) — the primary source, with default tables for each type of fossil fuel (coal, lignite, natural gas, etc.), expressed in tCO₂/TJ. Freely downloadable from ipcc-nggip.iges.or.jp.
- **EU ETS Monitoring and Reporting Regulation (MRR)** — Annex VI of Regulation (EU) 2018/2066 provides the “default” emission factors that EU ETS installations are authorised to use for reporting if they do not have their own laboratory analyses. It is probably the most relevant source if your aim is to replicate exactly the logic of the switching price in the EU ETS context.
- **DEFRA/BEIS UK Government GHG Conversion Factors** — updated annually and widely used outside the United Kingdom too for their clarity (gov.uk, search for “greenhouse gas reporting conversion factors”).
- **IEA (International Energy Agency)** — publishes average emission factors by fuel in its statistical reports (CO₂ Emissions from Fuel Combustion).

Typical indicative values: natural gas $\approx$ 0.20 tCO₂/MWh thermal; coal (depending on type, bituminous/lignite) $\approx$ 0.32-0.40 tCO₂/MWh thermal.

Heat rate / conversion efficiency (h_c, h_g)

Here variability is much higher, because it depends on the specific technology of the plant (a latest-generation CCGT is much more efficient than an old subcritical coal plant):

- **IEA — World Energy Outlook / Power Generation Efficiency database** — provides average efficiencies by plant type and geographical area.
- **ENTSO-E (European Network of Transmission System Operators)** — publishes aggregate data on the European generation fleet, useful for estimating a “system average” efficiency rather than that of a single plant.
- **EIA (U.S. Energy Information Administration)** — if you are interested in a US reference, it publishes average heat rates by plant type (eia.gov, “average heat rates”).

- **Technical reports from individual operators/turbine manufacturers** (Siemens Energy, GE Vernova, etc.) for the efficiency of specific latest-generation plants, if you need a precise figure rather than a sector average.
- **Energy market analysts** (Argus, Platts/S&P Global Commodity Insights, ICIS) often publish, alongside clean dark/spark spread quotes, the standard efficiency assumptions used in the calculation (typically 35-40% for coal, 50-55% for a modern CCGT), which is convenient because it gives you values directly consistent with the spreads quoted on the market.

A practical tip

If your aim is simply to check the order of magnitude of the switching price (not a precise regulatory calculation linked to a real plant), the standard values most often cited in the academic literature and in market reports are approximately:

- Coal efficiency: 35-38% (hence $h_c \approx 2.6-2.9$)
- CCGT gas efficiency: 50-55% (hence $h_g \approx 1.8-2.0$)
- $e_c \approx 0.34$ tCO₂/MWh thermal (coal)
- $e_g \approx 0.20$ tCO₂/MWh thermal (gas)

If, on the other hand, you need data linked to a specific plant or year for a rigorous analysis, the combination of the MRR (for emission factors, in a European context) and the IEA or ENTSO-E (for average efficiency) is probably the most robust and verifiable pair of sources.

8.8.2. The benchmarks: API#2, and from NBP to TTF

The calculation of the historical series given by Equation 1 can use as the gas reference the NBP (National Balancing Point), the British trading hub that is one of the most liquid gas markets in Europe or — better still — the TTF (Title Transfer Facility, the Dutch virtual market), now the most widely used benchmark for continental gas, and for coal the API#2 index of the Argus/McCloskey's Coal Price Index, the standard benchmark for coal imported into North-West Europe (CIF⁸ delivery Amsterdam-Rotterdam-Antwerp). Our recommendation is to use the TTF for gas and the API#2 as the reference for coal.

8.8.3. Why the theoretical price and the observed price do not coincide

The theoretical switching price E_t and the EUA price actually observed on the market never coincide perfectly. The first reason is technical: power plants are not all equally efficient, so each plant has its own specific switching point, and the market price reflects a heterogeneous average of these individual thresholds. The second reason is seasonal: the gas price has a marked winter seasonality, due to higher heating demand, which should be removed statistically (STL seasonal adjustment procedure) before comparing the two series.

8.8.4. The role of the TNAC: the structural medium-to-long-term component

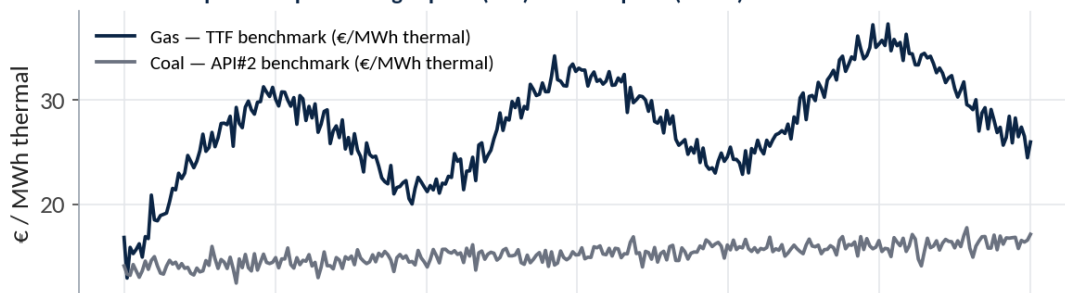
The switching price mainly explains the short-term dynamics of the allowance price, linked to current fuel costs. The TNAC (*Total Number of Allowances in Circulation*), the annual surplus indicator introduced in connection with the Market Stability Reserve, adds the structural medium-to-long-term component: it measures whether the system as a whole is in a situation of surplus or scarcity of allowances. The two indicators are complementary: even when the switching price would signal that switching to gas should already be worthwhile, a very high TNAC

⁸ Cost, Insurance and Freight.

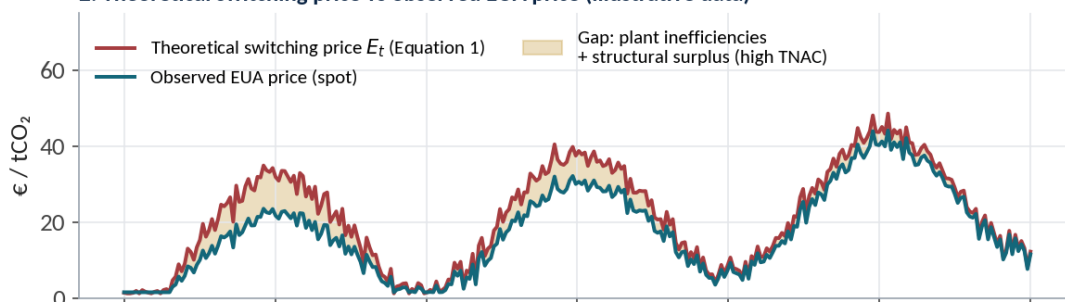
can keep the EUA price systematically below the theoretical switching price for prolonged periods — as historically observed during Phase II of the system, when the accumulated surplus exceeded two billion allowances. Every year, by 1 June, the European Commission publishes the TNAC value on the Market Stability Reserve page of its Climate Action website; this value automatically determines how many allowances are withheld from auctions (if the TNAC exceeds 833 million, 24% of the surplus is placed in the reserve) or released from the reserve (if it falls below 400 million). This is precisely the automatic supply adjustment mechanism introduced in Phase III of the EU ETS.

From fuel prices to allowance prices: switching price, observed EUA price and the role of the structural surplus (TNAC)

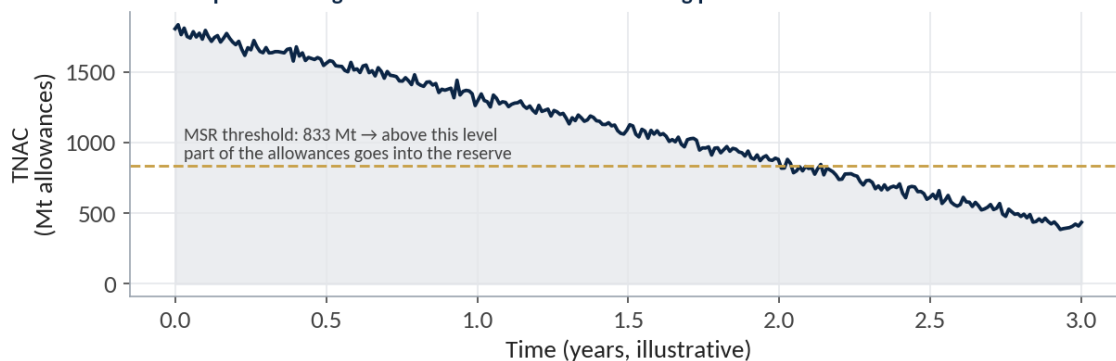
1. The two inputs of Equation 1: gas price (TTF) and coal price (API#2)



2. Theoretical switching price vs observed EUA price (illustrative data)



3. TNAC: the structural indicator — as the surplus shrinks, the EUA price converges towards the theoretical switching price



Note: series built with illustrative data to show how the switching price is formed (Equation 1). The switching price E_t is the CO₂ price that makes the Clean Dark Spread and the Clean Spark Spread equal; the gas benchmark used is the TTF (Title Transfer Facility), the European standard for continental gas, and for coal the API#2 index.

Figure 14. — From the top: (1) the fuel prices that feed into Equation 1 (TTF and API#2); (2) the theoretical switching price E_t compared with the observed EUA price, with the gap highlighted; (3) the TNAC, which explains the persistence of that gap over time. Series built with illustrative data to show the mechanism described in this section: they are not real data.

The thread linking these five elements can be summarised in a logical sequence: the Clean Dark Spread and the Clean Spark Spread define the profit margin of the two generation technologies; Equation 1 calculates the CO2 price that equalises them, using as inputs the market benchmarks API#2 (coal) and TTF (gas, in place of the NBP); comparing this theoretical price with the EUA price actually observed reveals a persistent gap; and the TNAC provides the structural key to explaining the size and duration of that gap over time.

Concluding remarks

The path proposed proceeds in progressively narrowing concentric circles: from climate science (ch. 2) to international governance and the evolution of carbon markets (ch. 3), from general environmental policy instruments and their translation into European industrial policy (ch. 4), to the long-run relationship between economic growth and environmental constraints (ch. 5), to the perspective of the individual regulated firm, which must decide how to invest and trade under a carbon pricing regime (ch. 6), and finally to the infrastructure and fundamental drivers of the financial market for European Union Allowances (chapters 7 and 8). The last circle is that of the EUA as a genuine asset class, with its own derivatives market, its own institutional investor base and its own quantitative valuation models.

A theoretical thread runs through the entire report: the notion that economic decisions under uncertainty and (partial) irreversibility — whether a policymaker's choice between a tax and a permit, or a firm's choice between investing in clean technology and buying permits — must be assessed by explicitly taking into account the value of flexibility: the possibility of waiting, gathering new information and changing course. It is the same principle that underlies both the Weitzman theorem on the comparison between price and quantity under uncertainty (ch. 4) and the entire real options framework applied to environmental investment decisions (ch. 6).

A second, more empirical thread concerns the role of markets: despite their limitations (information asymmetries, risk of manipulation, the need for careful institutional design), tradable permit systems remain the most efficient instrument observed so far for achieving a given emission-reduction target at the lowest possible aggregate cost. The experience of the European Union between 1990 and 2024 — GDP up by more than 70%, net emissions down by 40% — is today the strongest empirical evidence in support of this thesis, although it must always be balanced against the need for distributional fairness (hence, for example, the Social Climate Fund introduced together with ETS2) and the recognition that some environmental goods escape, at least in part, full monetary valuation.

A third thread concerns the progressive **financialisation** of the European carbon market. European Union Allowances, born as administrative compliance permits, are now a tradable asset with a spot market, futures, options, calendar spreads, listed products and an ever-broader institutional investor base. This transformation has not replaced the original function of EUAs — internalising the social cost of CO₂ emissions — but has added to it a second function, that of a stand-alone component of investment portfolios, with its own risk-return drivers. The way in which these two functions continue to coexist — regulatory compliance on the one hand, financial asset class on the other — will probably be one of the most important themes in the next phase of the European, and perhaps the global, carbon market.

Glossary of key terms

Absolute decoupling — A situation in which greenhouse gas emissions fall in absolute terms even as GDP grows, as distinct from relative decoupling (in which only emission intensity per unit of output falls).

Additionality — The requirement that the emission reduction generated by a project (in the Clean Development Mechanism as in voluntary markets) must be additional to what would have happened anyway in a baseline (business as usual) scenario.

Article 6 (Paris Agreement) — Provision of the Paris Agreement governing international cooperation through market instruments (Art. 6.2, bilateral transfers; Art. 6.4, new multilateral mechanism) and non-market instruments (Art. 6.8).

Assigned Amount Unit (AAU) — Unit of emission allowance assigned to each Annex I country under the Kyoto Protocol, expressed in tonnes of CO₂ equivalent.

Banking / Borrowing — The possibility, in a cap-and-trade system, of carrying unused permits forward to future periods (banking) or of using future permits early in the current period (borrowing).

Cap-and-trade — An environmental regulatory system in which an authority sets an aggregate emissions ceiling (cap), divides it into tradable permits and allows regulated firms to trade them.

Carbon Border Adjustment Mechanism (CBAM) — European mechanism that progressively applies a carbon price to imports of certain goods (cement, steel, aluminium, fertilisers, electricity, hydrogen) to counter the risk of carbon leakage.

Carbon budget — The maximum cumulative quantity of greenhouse gases that can still be released into the atmosphere without exceeding a warming threshold considered safe, with a given probability.

Carbon leakage — The relocation of production (and the associated emissions) to jurisdictions with less stringent climate regulation, in response to an increase in the cost of carbon in a given country or area.

CDM (Clean Development Mechanism) — Flexible mechanism of the Kyoto Protocol that allowed an Annex I country to finance emission-reduction projects in a developing country, obtaining CERs; progressively replaced by the new mechanism under Article 6.4 of the Paris Agreement.

Clean Dark / Clean Spark Spread — Indicators measuring the theoretical profitability of power generation from coal-fired and gas-fired plants respectively, net of the cost of emission allowances.

Corresponding Adjustment — Accounting adjustment required by Article 6.2 of the Paris Agreement to avoid double counting of emission reductions transferred between States.

ETS2 — Second European emissions trading system, introduced by the Fit for 55 package, covering fuels used in buildings and road transport; separate from and not fungible with EUAs of the traditional EU ETS.

EUA (European Union Allowance) — Emission allowance traded within the EU ETS, equal to the right to emit one tonne of CO₂ equivalent.

European Green Deal — European Union growth strategy presented in 2019, aimed at making the economy climate-neutral by 2050.

Externality — The (positive or negative) effect of an economic activity on third parties, not reflected in the market price of the good or service that generates it.

Fit for 55 — European legislative package that translates the objectives of the European Climate Law into operational rules, including the reform of the EU ETS, ETS2 and CBAM.

Fuel switching — The substitution, in power generation, of coal with natural gas (which emits less), made more or less attractive by the relative price of the two fuels and by the price of emission allowances.

Global Stocktake — Five-yearly review mechanism, provided for by the Paris Agreement, of collective progress towards global climate goals.

Global Warming Potential (GWP) — Index measuring the relative greenhouse effect of a gas compared with CO₂ over a given time horizon, taking into account both the intensity of the effect and persistence in the atmosphere.

Grandfathering — Method of allocating emission permits free of charge to regulated firms, typically based on historical emission levels.

Linear Reduction Factor (LRF) — Annual reduction rate of the EU ETS cap; significantly increased under the Fit for 55 package.

Market Stability Reserve (MSR) — Automatic EU ETS mechanism that temporarily withdraws allowances from the market when there is an excessive surplus, and releases them in the event of scarcity.

Nationally Determined Contributions (NDCs) — Emission-reduction targets and related policies, set independently by each State party to the Paris Agreement and updated periodically.

Net Zero — A state of balance between anthropogenic greenhouse gas emissions and removals, the goal of the Paris Agreement for the second half of the century.

NPV (Net Present Value) — Investment appraisal criterion based on the discounted sum of expected cash flows, net of costs; it recommends investing if the result is positive, but ignores the value of decision-making flexibility.

Paris Agreement — International climate treaty adopted at COP21 (2015), based on Nationally Determined Contributions (NDCs) submitted independently by each State, with the aim of holding warming well below 2°C and pursuing efforts to limit it to 1.5°C.

Real option — Application of financial option pricing theory to real investment decisions (in physical capital, technology, permits), in order to take into account flexibility in timing, scale or abandonment.

Social Cost of Carbon (SCC) — Monetary value of the total economic damage caused by emitting one additional tonne of CO₂.

SSP (Shared Socioeconomic Pathways) — Family of climate scenarios introduced by the IPCC Sixth Assessment Report, which replaced the Representative Concentration Pathways (RCPs) as the main reference in climate modelling.

Tipping point — A threshold beyond which a climate or ecological system undergoes a rapid, often irreversible, change of state.

TNAC (Total Number of Allowances in Circulation) — Total number of EUAs available in the system and not yet used for compliance; the main indicator of the market's structural surplus and the driving variable of the Market Stability Reserve.

Voluntary Carbon Markets (VCM) — Unregulated markets in which companies and investors voluntarily buy carbon credits generated by emission reduction or removal projects to offset their residual emissions.

Weak / strong sustainability — Under weak sustainability, growth is sustainable if the aggregate capital stock (natural, physical, human) does not decline over time, regardless of its composition; under strong sustainability, certain components of critical natural capital must be preserved regardless of the level of other forms of capital.

Weitzman theorem — The result that, when abatement costs are uncertain, the optimal choice between a price instrument (tax) and a quantity instrument (permit) depends on the relative steepness of the social marginal benefit and marginal abatement cost curves.