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The market of carbon credits and biofuels

A European perspective

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Abstract

This thesis presents an analysis of possible strategies and solutions that could help in reducing global emissions and fighting climate change, one of the most difficult challenges that humanity has ever faced. The work considers multifaceted strategies to achieve this goal, focusing in particular on innovative tools, strategies and technologies such as carbon markets, biofuels, and carbon capture technologies.
First, microeconomic insights are used to derive the principle that decisions of parties responsible for greenhouse gases emissions should be aligned with their true costs, i.e. a cost should be placed on their harmful consequences. These ideas represent the foundations of current international climate regulations, of which an historical evolution is presented, highlighting the most important milestones. Notably, the Kyoto Protocol and the Paris agreement have opened the way to the creation of Emission trading systems. Different typologies of carbon markets (Cap and Trade and Baseline and Credit, regulated and voluntary) are outlined and the current status of carbon pricing initiatives in the world is presented. Special attention is given to the European ETS, which because of its market volume and significance has been since its inception a benchmark for other emission trading systems worldwide.
Subsequently, the role of biofuels in the energy transition is tackled, since they represent an alternative to fossil fuel, particularly useful to decarbonize the transportation sector. However, they still face technological barriers in achieving properties similar to those of fossil fuels, and sustainability pose concerns regarding raw material sourcing.
Finally, the emission offsetting potential of Carbon Capture Utilization and Storage is presented, discussing technologies like BECCS and DACS, but also nature-based solutions, like reforestation and afforestation, and enhanced natural solutions like Biochar. A combination of these strategies offers a powerful toolbox to achieve net zero emissions, especially in “hard to abate" sectors.

Keywords: Microeconomics; Emission trading systems; EU-ETS; Biofuels; Carbon capture utilization and storage; Biochar

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Nomenclature

Variables

a	Carbon allowances price
$\underline{a}$	Floor price
C	Cost
d_a	Permits demand
D_a	Total Permits demand
f	Share of permits allocated for free
F	Freely allocated emissions
N	Number of firms
p	Price
$\bar{p}$	Demand function intercept
q	Quantity produced
$\bar{Q}$	Number of permits issued by the regulator
S	Supply
x	Proportion of relocating firms
z	Abatement efforts

Greek letters

α	Linear demand function angular coefficient parameter
β	Choice change speed parameter
Δ	Difference
θ	(In)efficacy of abatement technologies
Π	Profit

Acronyms

AAU	Assigned amount unit
ACR	American carbon registry
CDM	Clean development mechanism
BECCS	Bioenergy with carbon capture and storage BECCS
CAR	Carbon action reserve
CCB	Climate, community and biodiversity standards
CCUS	Carbon Capture Utilization and Storage CCUS
CER	Certified emission reduction
CH_4	Methane
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
COP	Conference of the parties
CPI	Carbon pricing initiative
CRC	Carbon Removal Credits
DAC	Direct Air capture
DACS	Direct Air capture and storage
DME	Carbon dimethyl ether
ERU	Emission Reduction Unit
ETBE	Ethyl Tertiary Butyl Ether
ETS	Emission trading system

EU	European Union
GHG	Greenhouse gas
GDP	Gross domestic product
FAME	Fatty Acid Methyl Ester
GHG	Greenhouse gases
GS	Gold standard
IET	International emissions trading
HEFA	Hydro processed Esters and Fatty Acids
HVO	Hydrotreated Vegetable Oil
ILUC	Indirect Land Use Change
ITMO	Internationally transferred mitigation outcomes
JI	Joint implementation
L-DAC	Liquid sorbent direct air capture
LNG	Liquefied natural gas
LUF	Land use and Forest
MRV	Measuring, reporting and verification
MSR	Market Stability Reserve
NDC	Nationally determined contributions
NET	Negative Emission Technologies
RED	Renewable Energy Directive
RFNBOs	Renewable fuels of non-biological origin
SAF	Sustainable aviation fuel
S-DAC	Solid sorbent direct air capture
TCP	Technology Collaboration Program
TPES	Total primary energy supply
UN	United nations
UNCED	UN conference on environment and development
VCM	Voluntary carbon market
VCS	Verified carbon standard
WTO	World Trade Organization

Subscripts and superscripts

eq	Equivalent
f	Fix
h	Home
r	Relocating
t	Time
v	Variable
$*$	Optimal

Content of the thesis

Chapter 1 introduces the issue of climate change by presenting recent data on global greenhouse gases emissions and on the resulting harmful consequences for global warming. This data highlights the need to develop new technologies and strategies to address these challenges and the use of carbon markets, biofuels and carbon capture technologies are indicated as valuable tools in this sense.

Chapter 2 examines the complexities of climate change through the lenses of microeconomic, exploring how it offers insight into the intricacies of climate change and suggests potential solutions. To align decisions of parties responsible for greenhouse gases emissions with the true costs of climate change, microeconomics suggests placing a price on the harm inflicted by emissions. Emissions standards and fees, Pigouvian taxes and tradable permits are approaches that governments can use to achieve this objective.

Chapter 3 introduces an overview of international climate regulations like the Kyoto Protocol and the Paris agreement, which have played a fundamental role in reducing greenhouse gas emissions and that opened the way to the creation of Emission trading systems. Emission trading systems typologies are presented, including Cap and Trade and Baseline and Credit systems. Moreover, division of carbon markets into mandatory regulated markets and voluntary carbon offset markets is discussed. In this context, the utility of these regulatory frameworks in promoting sustainable global climate actions and setting the stage for collaborative efforts in emissions reduction is discussed.

Chapter 4 delve into the role that biofuels in the energy transition. Biofuels offer a low-carbon alternative for current transportation technologies but face technological barriers in achieving properties similar to those of fossil fuels, and sustainability concerns regarding raw material sourcing. Despite these challenges, biofuels are critical to achieve Net Zero Emissions, as highlighted by the anticipated growth in demand. However, economic fluctuations and geopolitical influences impact the biofuel landscape, requiring government to implement adaptable and robust diffusion strategies.

Chapter 5 contains details on Carbon Capture Utilization and Storage highlighting its potential in offsetting emissions, particularly in “hard to abate" sectors.
CCUS encompasses diverse technologies, notably BECCS and DACS, showing promise but with distinct characteristics. BECCS, is more cost-effective due to higher pre-capture CO_2 concentrations, while DACS, offers location flexibility but demands significant energy resources.
Nature-based solutions, like reforestation and afforestation, although pivotal, are characterized by substantial land requirements. Finally, Biochar's potential for carbon sequestration is highlighted, emphasizing its ability to remove significant CO_2 quantities from the atmosphere for long-term periods.
A combination of these strategies offers a powerful toolbox to achieve net zero emissions.

Chapter 6 summarizes the main achievements and conclusions of this work.

Finally, *Chapter 7* includes all the appendixes.

Chapter 1

General introduction

The global issue of climate change is presented in this chapter by laying out the increasing emissions and global warming trends. Recent global greenhouse gases emissions data is presented, as per capita, sector and region information, highlighting persisting increasing tendencies. The harmful consequences on global warming are shown through data on land and sea temperature changes in recent years. This data calls for urgent actions. The need to develop new technologies and strategies to address these challenges is discussed and the use of carbon markets, the diffusion of biofuels, and use of carbon capture technologies are indicated as valuable tools to mitigate the current climate crisis.

1.1 Context

Climate change is one of the most critical challenges that humanity has ever been confronted with. The warming of the planet threatens food security, freshwater supply, human health, and political stability worldwide. The effects of climate change, including sea level rise, droughts, floods, and extreme weather, will be more severe if actions are not taken to drastically reduce emissions of greenhouse gases (GHG) into the atmosphere.

The task is complicated by a growing world population, increased from 6 billion in the beginning of the century to 8 billion in 2022 and expected to reach 9.7 billion in 2050 [1]. This together with a continuous development of the global economy results in an energy demand growing worldwide at unrestrained rates. Indeed, researchers forecasted global energy demand to double or even triple until 2050 [2]. Achieving climate neutrality has become a shared goal among numerous national governments and currently most developed countries are aiming for climate neutrality by 2050. This aspiration is echoed by two rapidly growing economic giants, China (targeting 2060) and India (2070).

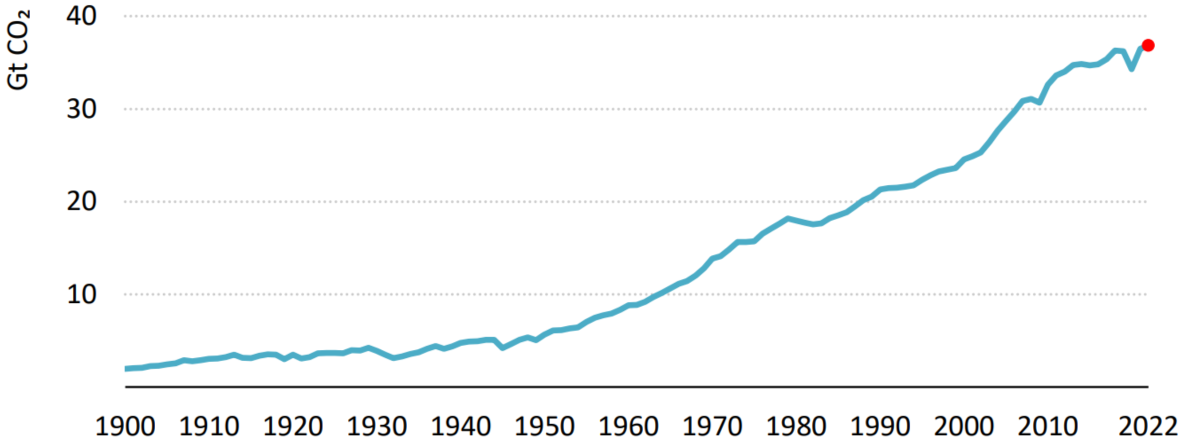


Fig. 1.1 – Global CO_2 emissions from energy combustion and industrial, 1900-2022 [3].

Nevertheless, according to an IEA's analysis [3], global carbon dioxide (CO_2) emissions from energy combustion and industrial processes grew by 0.9% in 2022, equivalent to 321 million tons, reaching a new historical peak of 36.8 gigatons (**Fig. 1.1**). This increase follows two years of fluctuation due to the Covid-19 pandemic, which disrupted energy demand patterns. In 2020, emissions witnessed a 5% reduction, while in 2021, they rebounded beyond pre-pandemic levels, surging by over 6%.

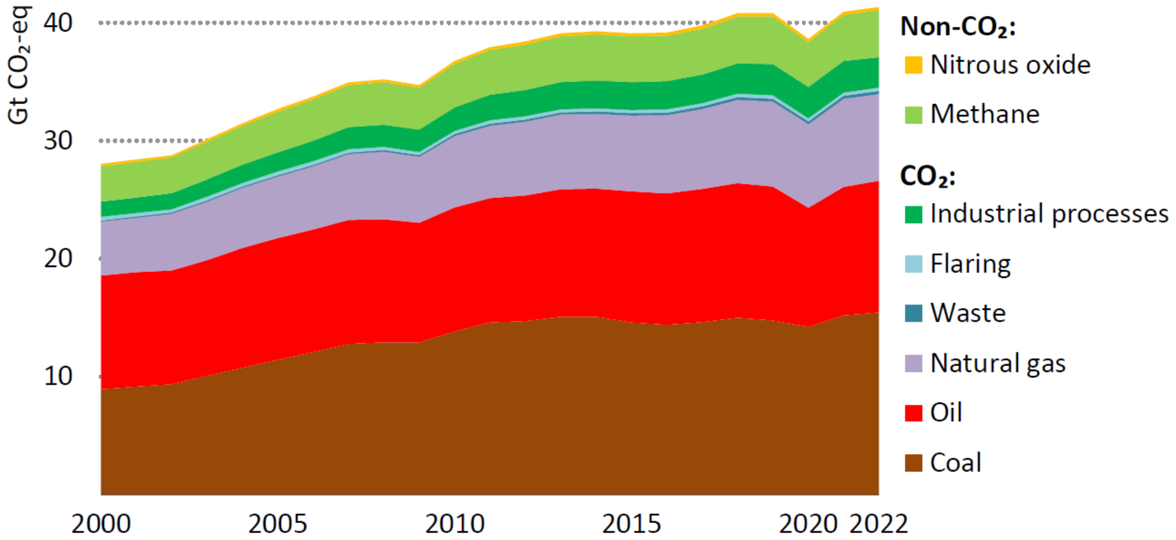


Fig. 1.2 – Global energy-related greenhouse gas emissions, 1900-2022 [3].

CO_2 emissions from energy combustion and industrial process made up 89% of energy-related greenhouse gas emissions in 2022. Indeed, total energy-related greenhouse gas emissions reached an all-time high of 41.3 gigatons CO_2 equivalent (CO_2eq), as shown in **Fig. 1.2**. The remaining 10% comprised non-combustion methane (CH_4) emissions, originating mainly from losses and venting in extraction facilities, predominantly associated with onshore oil and gas operations. Despite elevated natural gas prices having improved the cost-effectiveness of methane recovery technologies, methane emissions in 2022 increased to nearly 135 million tons of CH_4 (approximately 4 gigatons CO_2eq).

Olivier and Peters [4] examined global emissions data across various countries highlighting that the six largest contributors to GHG emissions consist of five individual countries and the European Union. Specifically, these are China (26%), the United States (13%), the European Union (9%), India (7%), the Russian Federation (5%), and Japan (nearly 3%), as shown in **Fig. 1.3**. This collective group represents a significant portion, accounting for 62% of total global greenhouse gas emissions and 67% of total global CO_2 emissions. These countries encompass 51% of the global population, 65% of the Gross Domestic Product (GDP), and 64% of the Total Primary Energy Supply (TPES).
Delving deeper into the emissions data for these six nations, a clear trajectory emerges [4]. In 2019, emissions saw an increase in three countries. Specifically, India witnessed a rise of approximately 50 MtCO_2eq or +1.4%, while the Russian Federation experienced an uptick of 20 MtCO_2eq or +0.9%, meanwhile China's emissions surged by a substantial 350 MtCO_2eq or +2.2%.
In contrast, the United States, Japan and the European Union experienced a decrease in emissions during the same period. The United States, for instance, achieved a reduction of 110 MtCO_2eq or, -1.7%, while Japan saw a decline of 20 MtCO_2eq, or -1.6%. The EU demonstrated a noteworthy drop of 140 MtCO_2eq, or -3.0% of its total emissions.
Further scrutiny within the European Union reveals a nuanced picture. Several countries, including Germany, Poland, Spain, Italy, the United Kingdom, France, and the Netherlands, contributed to the overall reduction in emissions. Conversely, Austria and Sweden experienced the most significant increases in emissions during 2019, both with a +2.7% uptick.

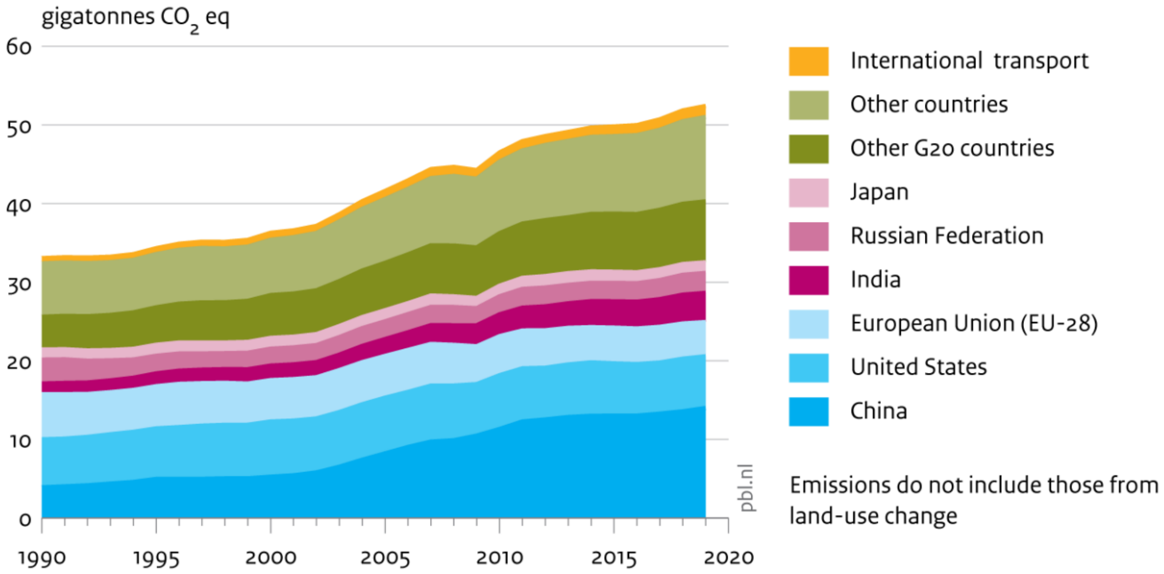


Fig. 1.3 – Global GHG emissions, per country and region [4].

Fig. 1.4 shows per capita greenhouse gas emissions [4] for the five major emitting countries, the EU, the rest of the world, and the global average. Apart from India, all major emitters exhibit per capita emission levels notably higher than both the global average and those of the rest of the world. China ranks fourth (despite leading in absolute emissions). While CO_2 equivalent emissions per capita in the United States have consistently declined since 2000 (from 25 tCO_2eq/cap to around 20 tCO_2eq/cap in 2019) they are still the highest among the top five emitting countries. However, those of Australia (30.7 tCO_2eq/cap), Canada (21.8 tCO2eq/cap), and Saudi Arabia (21.1 tCO_2eq/cap), which are not shown in **Fig. 1.4** are even higher.

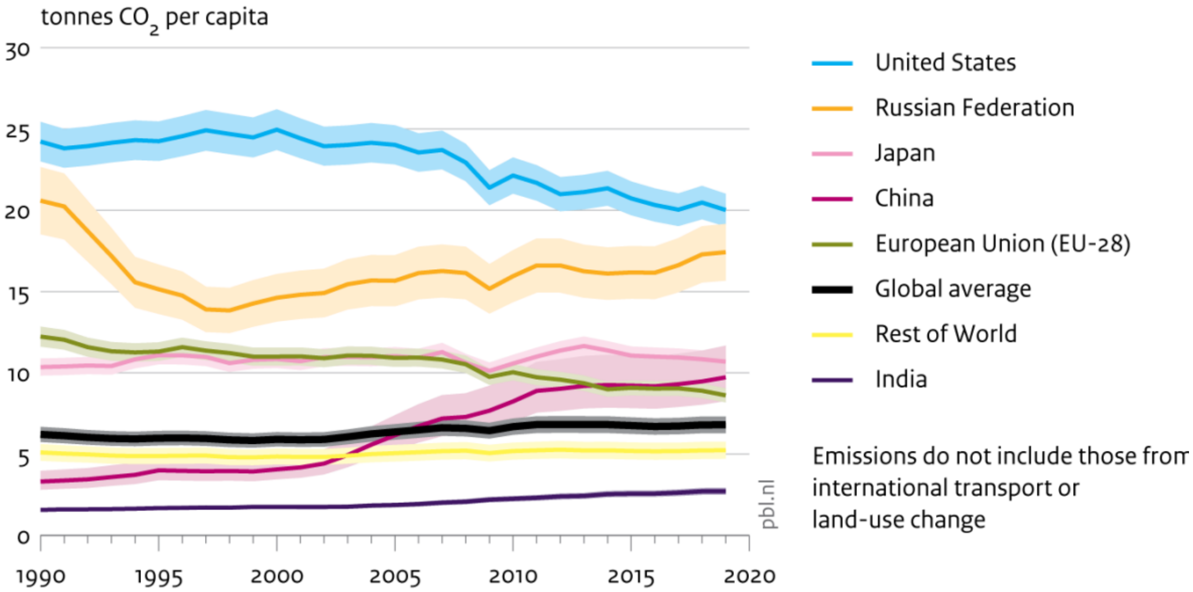


Fig. 1.4 – GHG emissions, per capita, per country and region [4].

Concerning Italy, overall greenhouse gas emissions showed a reduction of 19.9% in 2021 in comparison to 1990 levels, passing from 519 to 418 million tCO_2eq [5]. This change was primarily driven by a notable reduction in CO_2 emissions, contributing 80.8% to the overall decrease with a recorded value in 2021 23.2% lower than that in 1990 (**Table 1.1**). This reduction, observed in particular since 2008 (**Fig. 1.5**), is a consequence of both the reduction in energy consumption and industrial production caused due to the economic crisis and the delocalization of some industrial production, but also to the growth in energy production from renewable sources and an increase in energy efficiency. The drop in emissions recorded following the pandemic also weighed. The increase in emissions reported in 2021 is also a result of the recovery of mobility and economic activities after the pandemic period and trends of GHG emissions in 2022, are estimated in line with what was emitted in 2021. The majority of GHG emissions, accounting for around 80% of the total were attributable to the energy sector (**Fig. 1.6**). In particular, CO_2 emissions from this sector decreased by around 22% from 1990 to 2021 (**Table 1.2**). The transport sector, representing 31% of total energy sector emissions, recorded a 1.1% increase from 1990 to 2021. Other sectors, including residential (accounting for 25.0% of the total energy sector emissions in 2021), saw a 6.4% increase in emissions.

Emissions from the industrial process sector exhibited a decrease of 18.9% from 1990 to 2021, primarily attributed to reductions in the chemical sector and emissions from mineral and metal production. Conversely, emissions of fluorinated gases in this sector increased significantly by 372%, constituting 50.5% of total sector emissions.

Table 1.1 – Total Italian greenhouse gas emissions by gas for the period 1990-2021 (kt CO_2eq) [5].

Emissions (kt CO_2eq)	**1990**	**2000**	**2010**	**2015**	**2017**	**2018**	**2019**	**2020**	**2021**
CO_2 excluding LULUCF	438,904	470,524	436,534	361,936	353,419	349,827	340,403	303,281	337,230
CO_2 excluding LULUCF	433,214	447,552	394,075	317,385	327,934	304,086	297,929	269,900	308,306
CH_4 excluding LULUCF	54,975	57,706	52,690	49,316	48,784	47,972	46,762	47,513	47,087
CH_4 excluding LULUCF	56,416	58,506	53,083	49,611	50,476	48,144	46,965	47,885	48,065
N_2O excluding LULUCF	24,193	26,923	18,090	16,788	16,958	16,893	16,691	17,346	17,193
N_2O excluding LULUCF	24,954	27,541	18,472	17,079	17,452	17,292	17,124	17,811	17,666
HFCs	372	2,803	14,325	15,630	16,514	16,928	17,019	16,035	15,388
PFCs	2,615	1,363	1,377	1,529	1,191	1,502	915	499	395
Mix di HFCs e PFCs	NO,NA	24	24	24	24	23	23	22	25
SF_6	421	621	405	485	428	464	444	257	258
NF_3	NA,NO	13	20	28	23	22	18	16	15
Total (excl. LULUCF)	**521,480**	**559,978**	**523,466**	**445,736**	**37,341**	**433,631**	**422,276**	**384,970**	**417,591**
Total (with LULUCF)	**517,992**	**538,424**	**481,781**	**401,772**	**414,04**	**388,460**	**380,439**	**352,425**	**390,118**

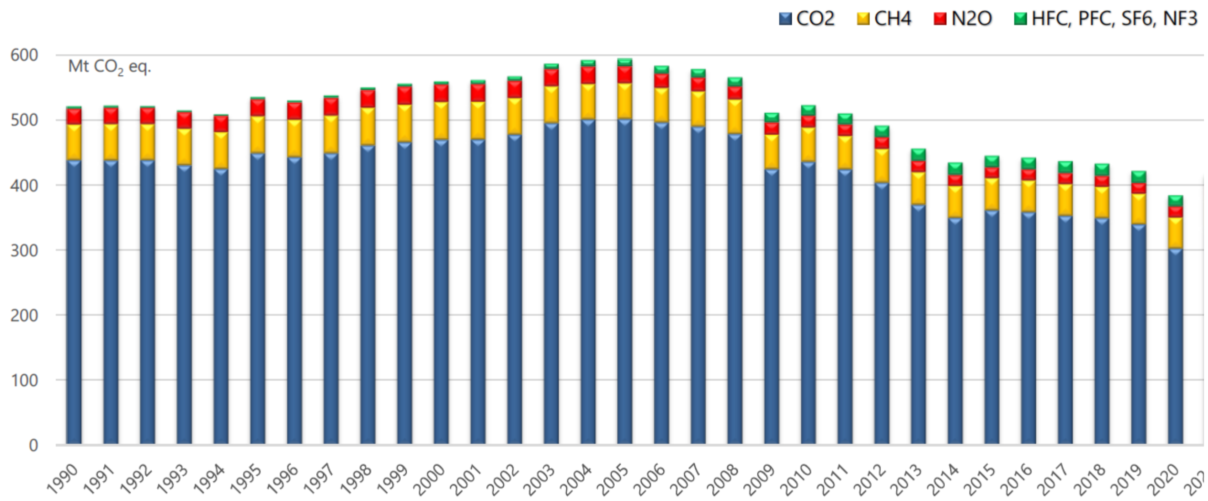


Fig. 1.5 – Italian GHG emissions from 1990 to 2021 by gas [5].

Table 1.2 – Total Italian greenhouse gas emissions by sector for the period 1990-2021 (kt CO_2eq) [5].

Emissions (kt CO_2eq)	**1990**	**2000**	**2010**	**2015**	**2017**	**2018**	**2019**	**2020**	**2021**
Energy	425,548	460,326	429,904	359,966	350,969	346,504	336,391	300,048	332,832
Industrial Processes	39,257	38,368	38,960	33,328	33,881	34,927	34,038	31,040	31,852
Agriculture	37,676	37,185	32,225	32,102	32,581	32,306	32,190	33,427	32,717
LULUCF	-3,489	-21,554	-41,685	-43,964	-23,298	-45,171	-41,837	-32,545	-27,473
Wastes	18,999	24,099	22,377	20,340	19,911	19,893	19,657	20,456	20,190
Total (with LULUCF)	**517,992**	**538,424**	**481,781**	**401,772**	**414,043**	**388,460**	**380,439**	**352,425**	**390,118**

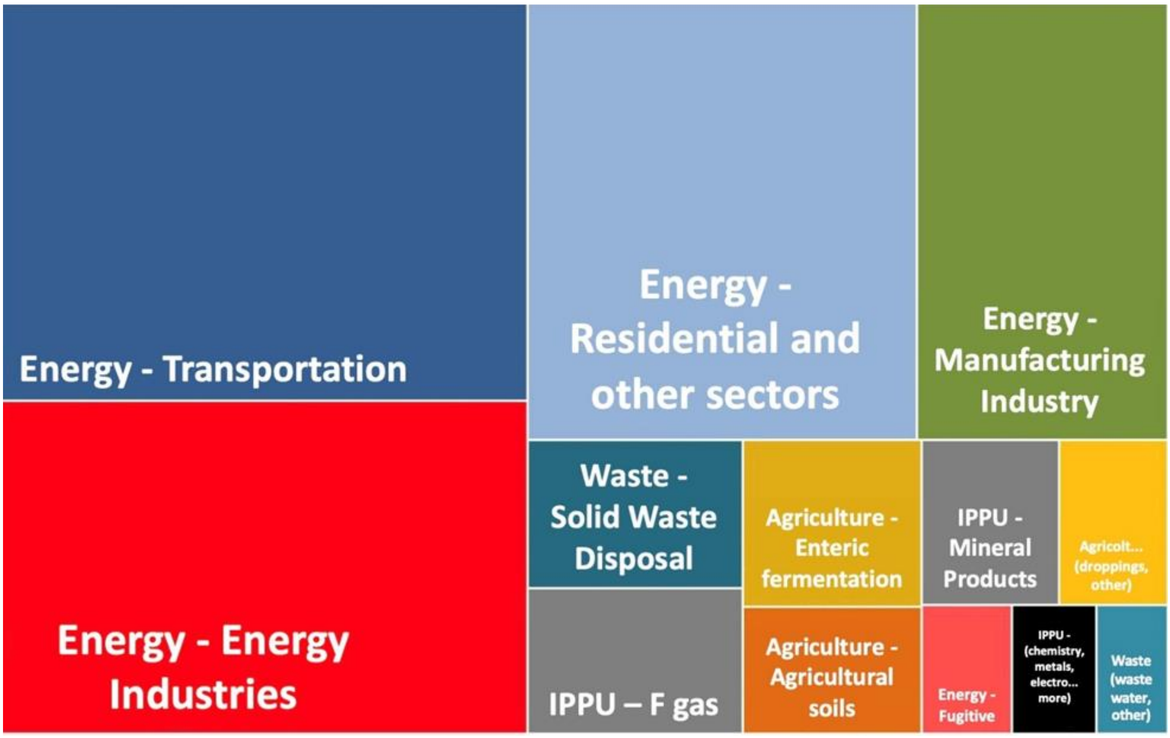


Fig. 1.6 – Italian GHG emissions in 2021 by sector categories (proportion estimated based on the contribution in CO_2eq equivalent) [5].

In agriculture, emissions predominantly relate to CH_4 and N_2O, representing 64.9% and 33.7% of the sector's total, respectively. The observed decrease in emissions from 1990 to 2021 (-13.2%) is mainly attributed to reductions in CH_4 emissions from enteric fermentation (-14.2%) and N_2O from agricultural soils (-7.8%).

For land use changes and forestry, total removals of CO_2 equivalent experienced a significant increase from 1990 to 2021, with CO_2 constituting almost all (95.2%) of the sector's emissions and absorptions.

Lastly, emissions from the waste sector increased by 6.3% from 1990 to 2021, primarily due to elevated emissions from landfill disposal (14.7%), representing 77.6% of waste emissions. The most prominent GHG in this sector is CH_4, constituting 91.9% of emissions, with a 7.1% increase from 1990 to 2021. N_2O emissions increased by 33.2%, while CO_2 emissions decreased by 83.2%, representing 7.7% and 0.4% of the sector, respectively.

On a national level, the largest GHG emissions contribution is due to CO_2, followed by CH_4, N_2O and F-gases. The contribution of these gases to total emissions varied over the period 1990-2021, as shown in **Fig. 1.5**.

The emission categories that contribute most to total GHG emissions in Italy are those of the Energy sector. As shown in **Fig. 1.6**, energy, manufacturing, transport, residential industries and other sectors are overall responsible, for almost 80% of total emissions at the national level in 2021. The Agriculture sector, Industrial Processes and Use of Other Products (IPPU) are responsible for 7.8% and 7.6%, respectively, while the Waste sector contributes to the remaining 4.8% of total emissions.

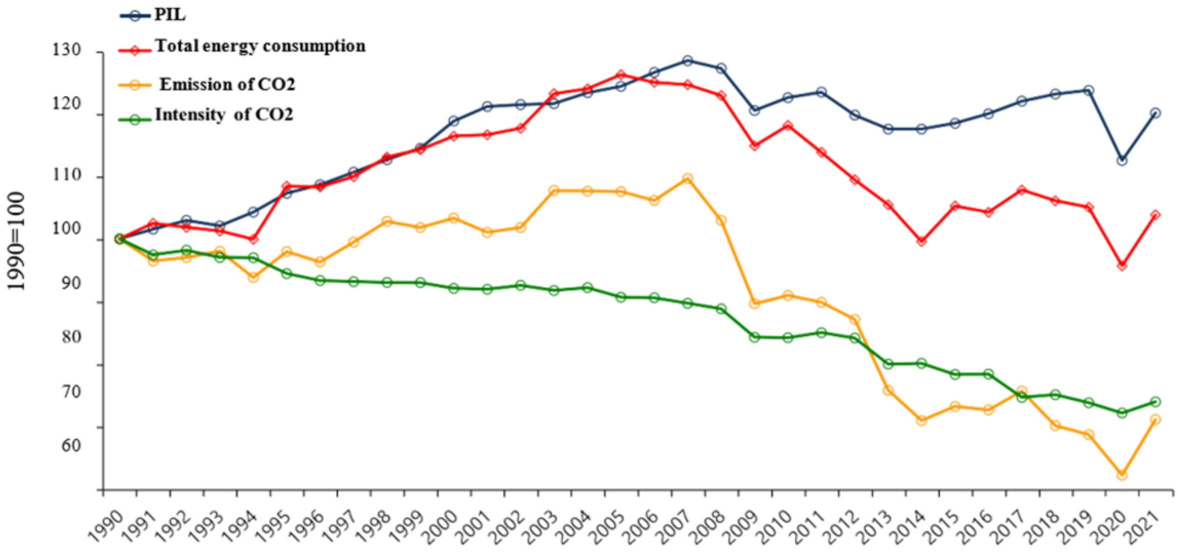


Fig. 1.7 – Indexed CO_2 emissions and energy-economic indicators for Italy from 1990 to 2021 [5].

CO_2 emissions in the 1990s essentially reflected energy consumption. Only in recent years has a decoupling been observed between the consumption and emissions curves, mainly following the replacement of fuels with a high carbon content with methane gas in the production of electricity and in industry; in recent years the increase in the use of renewable sources has led to a notable reduction in CO_2 intensity, as shown in **Fig. 1.7**. In 2021, after the sharp drop in emissions and the slowdown in economic growth due to the COVID pandemic crisis, there has been a recovery in GDP, accompanied by a recovery in energy consumption and emissions.

Regarding per capita emissions [6], Italy exhibits values approximately 18% lower than the European average, and countries like Germany, Austria and Denmark, aligning with other major countries such as France, UK and Sweden.

It is noteworthy that on a global scale, there are significant disparities with African nations (e.g., Rwanda, where per capita emissions are only 1/10th of Italy) and on middle Easter countries, such as Qatar, where on the other hand, per capita emissions are 10 times higher than those in Italy.

1.1.1 Impact on climate change

All of this has profound climate implications, culminating in 2022 marking the fifth warmest year on record, although the fourth-eighth warmest years are very close together and the last eight years have been the warmest on record (**Fig. 1.8**).

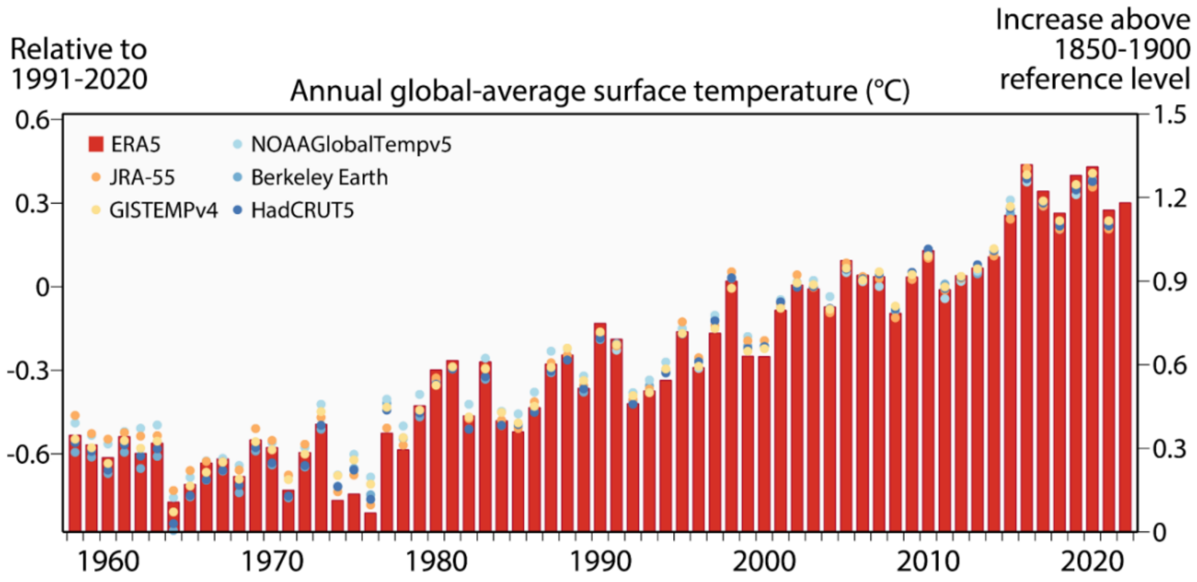


Fig. 1.8 – Annual averages of the estimated global surface temperature [7].

Indeed, the hottest years documented thus far were 2016, 2020, 2019, 2017, and 2022. Particularly significant, 2016 emerged as the warmest year in the last 140 years characterized by a +0.99 °C increase in average surface temperatures across land and oceans compared to preceding years. Europe saw its second warmest year on record, only surpassed by 2020, and experienced its hottest summer ever recorded. Persistent low levels of rainfall, in combination with high temperatures led to widespread droughts, while extreme events were experienced more frequently across the world.

Regrettably, the circumstances do not appear to have ameliorated in 2023. July of 2023 witnessed the most significant temperature surge ever documented since the pre-industrial era [8]. The consequent revision in temperature trend projections lead to forecasting that global warming will reach 1.5 °C by the year 2035, as shown in **Fig. 1.9**.

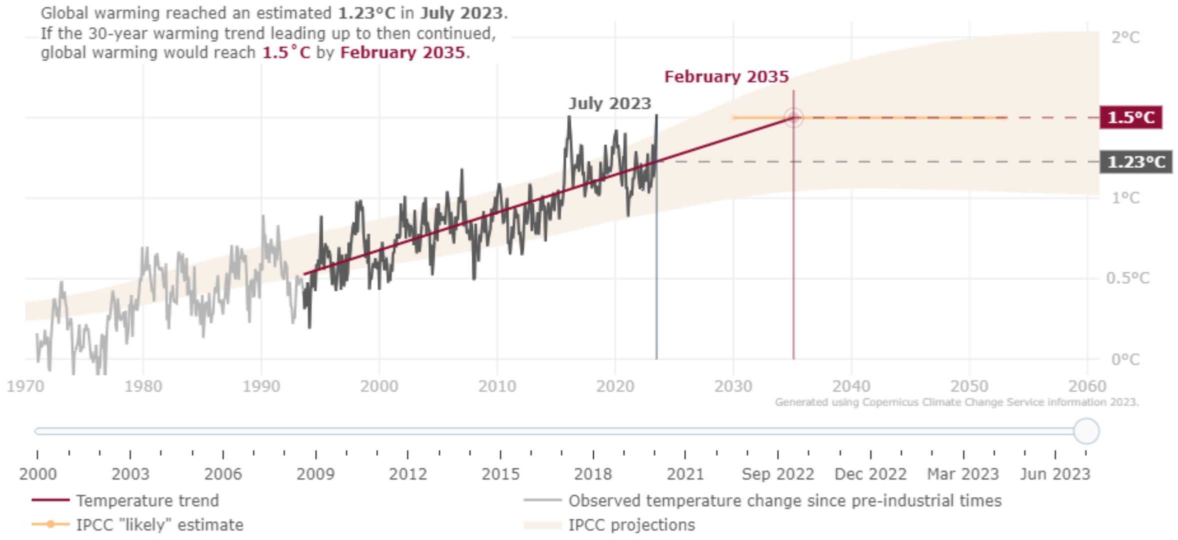


Fig. 1.9 – Copernicus global temperature trend monitor [8].

1.2 Conclusions

The evidence presented in this chapter clearly shows that urgent action is imperative. Climate change poses a monumental threat, impacting various facets of human existence ranging from food security to political stability. In this context, the development of innovative strategies, solutions and technologies is of vital importance. The analysis of the problem through the lenses of Microeconomics is presented in *Chapter 2*, which highlights how tradable pollution rights (leading to the creation of carbon market) are an important tool in the hands of Regulators. Indeed, as discussed in *Chapter 3*, carbon markets offer a promising avenue to incentivize emission reductions where it is more cost-effective. Implementing robust mechanisms to trade carbon credits can encourage industries to adopt greener practices, thereby reducing their carbon footprint. Simultaneously, the development and widespread adoption of biofuels, presented in *Chapter 4* stand as viable alternatives to traditional fossil fuels, offering a pathway to reduce emissions, especially in sectors like transportation.

Moreover, although priority is on the diffusion of renewables, the advancements of carbon capture technologies hold great potential to offset emissions and will play a pivotal role in future climate mitigation strategies.

The integration of these strategies and technologies could significantly contribute to lowering the overall greenhouse gas emissions and stands as a potential path forward amidst the concerning trends in emissions and climate change.

Chapter 2

Pollution as a market failure

The second chapter of this thesis examines the complexities of climate change through the lenses of microeconomics. The challenge of addressing climate change is represented by the vast number of pollution sources and the financial obstacles linked to greenhouse gas emissions reduction. This chapter explores how microeconomics offers insight into the intricacies of climate change and suggests potential solutions. Parties responsible for greenhouse gas emissions often overlook the environmental damage resulting from their actions, negatively impacting others. To align decisions with the true costs of climate change, microeconomics suggests placing a price on the harm inflicted by emissions. Emissions standards and fees, Pigouvian taxes and property rights are approaches governments can use to address externalities and optimize resource allocation. Finally, the concept of tradable pollution rights is explored. Tradable permits are allocated and exchanged among companies, enabling cost-effective pollution reduction.

2.1 Microeconomics and climate change

According to the Intergovernmental Panel on Climate Change, the common conclusion of a wide range of fingerprint studies conducted over the last years is that observed climate changes cannot be explained by natural factors alone [9].

But if the diagnosis of climate change is unequivocal, what to do about it is less obvious. The scale of pollution sources requiring control is staggering. Additionally, addressing the issue of greenhouse gases (GHG) emissions reduction presents significant financial challenges. Given these circumstances, the task of fighting global climate change may seem insurmountable.

Microeconomics provides valuable insights into the complexity of climate change and offers potential solutions. The difficulty lies in the fact that the parties responsible for GHG emissions often disregard the environmental harm caused by their decisions, affecting others negatively.

To induce parties to make decisions that reflect the real costs of climate change, a way to put a price on the harm that GHG emissions cause to the climate and the economy. Microeconomic principles can be employed to achieve this objective. An example is the emission cap-and-trade system adopted by the EU, European Union (EU) Emissions Trading System, described in detail in *Section 3.5*.

A cap-and-trade system applies microeconomics to achieve pollution reduction at minimal expense. It involves setting caps on the amount of specific greenhouse gases, such as CO_2, that can be emitted from particular sources. CO_2 permits are then allocated to companies, granting them permission to emit a specific quantity of CO_2 equivalent over a defined period. Companies are allowed to trade these permits freely within an open market. The concept behind this system is that companies capable of reducing their CO_2 emissions below their assigned caps at a low cost (e.g., by implementing pollution control technology) can sell their excess allowances to other companies for whom emission reduction is more expensive. The beauty of this market-based approach lies in achieving emission reductions at the lowest possible cost. Additionally, the government does not need to identify which companies can reduce pollution more cost-effectively since the free market facilitates this process. Companies with low compliance costs can sell permits, while those with high compliance costs can purchase them. Furthermore, by gradually reducing the supply of permits over time, the government can effectively decrease pollution while minimizing costs.

2.2 Partial equilibrium analysis in competitive markets

Partial equilibrium analysis focuses on determining the equilibrium price and output within a single market, assuming that the prices in all other markets remain constant. On the other hand, to examine how changes in one market affect all markets simultaneously, a general equilibrium model is required. By employing a general equilibrium analysis, one can determine the equilibrium prices and quantities across all markets simultaneously. It is important to note that the conclusions drawn from a partial equilibrium analysis may differ from those obtained through a general equilibrium approach. Nonetheless, the partial equilibrium framework often provides valuable insights into the primary effects of government intervention.

Partial equilibrium analysis can for example be used to explore competitive markets. In a perfectly competitive market, both producers and consumers are small entities, behaving as price takers due to their fragmentation within the market. Consumers possess complete information about the product and its price. Furthermore, competitive markets are devoid of externalities, which occur when the actions of consumers or producers result in costs or benefits that are not reflected in the market price of the product.

One of the remarkable features of a competitive market is that in equilibrium, it allocates resources efficiently. **Fig. 2.1** shows that in a competitive equilibrium, the market price is P_A with a quantity Q_A exchanged in the market (point A). The sum of consumer surplus (ADF) and producer surplus (AFG) is ADG, the area below the demand curve and above the supply curve S.

Producing a smaller quantity, for example Q_B, the demand curve shows that there would be consumers willing to pay P_B. However, since the supply curve indicates the marginal cost of producing the next unit in the market, it can be inferred that it only costs society C_B to produce that unit. Thus, total surplus would be increased by P_B-C_B if the additional unit is produced. When the demand curve lies above the supply curve, the total surplus will increase if another unit is produced. On the other end, when the demand curve lies below the supply curve, total surplus can be increased by cutting back the quantity of the goods produced.

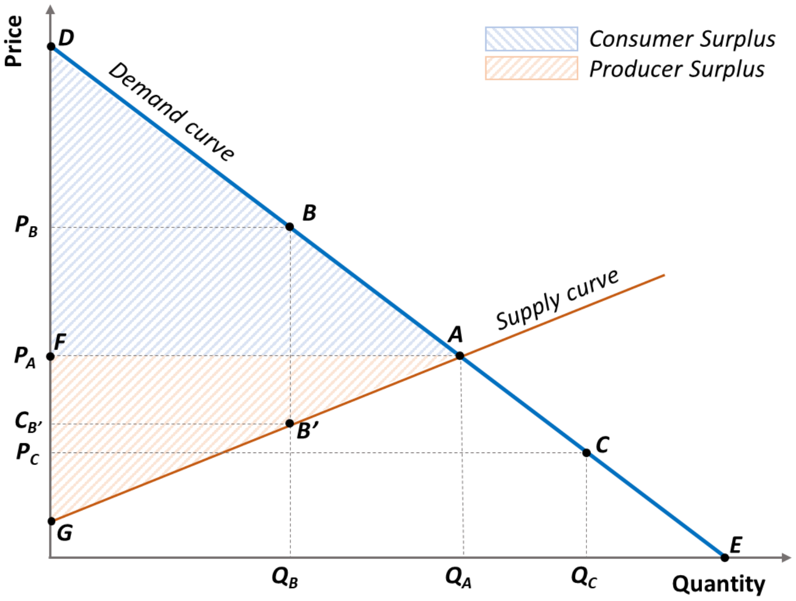


Fig. 2.1 – Economic efficiency in a competitive market. Adapted from [10].

This shows that any production level other than Q_A will lead to a total surplus lower than AFG. It follows that the efficient level of output is the one determined by the intersection of the supply and demand curves, that is, the perfectly competitive equilibrium [10].

In a market characterized by perfect competition, each producer pursues its own self-interest by deciding whether to participate in the market and, if so, determining the optimal quantity to produce in order to maximize its own producer surplus. Similarly, each consumer acts in their own self-interest by maximizing utility to determine the quantity of the good they should purchase. There is no entity directing producers and consumers on how to behave in order to achieve the efficient level of output. Nevertheless, the output produced maximizes net economic benefits, i.e., the total sum of surpluses. This concept was eloquently described by Adam Smith in his influential work published in 1776, "An Inquiry into the Nature and Causes of the Wealth of Nations" [11], where he metaphorically referred to the mechanism as an "Invisible Hand" guiding a competitive market toward the efficient levels of production and consumption [11].

2.3 Externalities

In economics, an externality refers to a situation where the actions of an individual or entity impact the well-being of others, either positively or negatively, without being fully accounted for by market prices. The failure to incorporate certain costs and benefits associated with individual decisions in market demand and supply results in a resource allocation that is not optimal.

Externalities can be categorized as either positive or negative, depending on their effects. A positive externality occurs when an action yields favorable outcomes from a societal perspective. For example, vaccinations not only protect individuals from diseases but also contribute to the health of the community by reducing disease transmission.

Conversely, negative externalities result in adverse effects on society. Smoking is an instance of negative externality as it imposes health costs on both smokers and non-smokers exposed to second-hand smoke. Such externalities can arise in both production and consumption contexts.
For instance, a company's development of new technology that benefits other businesses by enhancing productivity and lowering production costs demonstrates a positive production externality. From a production standpoint, pollution is an example of a negative externality. For example, if a factory discharges waste into a river, leading to the death of a portion of the fish population this will cause financial and recreational losses for downstream fishermen. If these losses are uncompensated, the upstream industry is said to create an external cost, also known as a negative externality [12].

Externalities are considered market failures, even in the ideal case of perfect competition, as the market fails to efficiently allocate productive resources, resulting in costs to society. According to Pearce and Turner [13], negative externalities take place in presence of the following two conditions:

- An activity undertaken by one agent causes a loss of well-being to another agent.
- The loss of well-being is uncompensated.

If the loss of well-being is compensated by the agent causing it, then the externality effect is said to be internalized.

2.3.1 Partial equilibrium analysis in the presence of pollution externalities

In the presence of negative externalities, the marginal social cost (MSC) surpasses the marginal private cost (MPC) by the magnitude of the marginal external cost (MEC), as shown in **Fig. 2.2**.

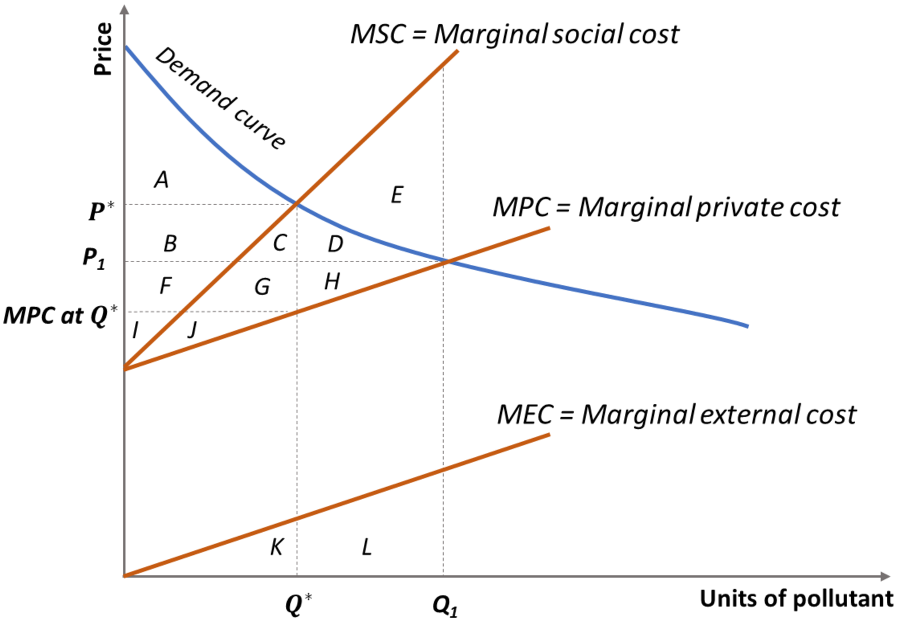


Fig. 2.2 – Optimal quantity in the presence of externalities. Adapted from [10].

In scenarios where firms are not held accountable for these external expenses, the market's supply curve corresponds to the MPC. This leads to an equilibrium price of P_1 and a corresponding market output of Q_1. However, in an optimal societal scenario, businesses would be obliged to cover the costs associated with externalities, resulting in a different market price denoted as P^* and a corresponding quantity labeled as Q^*. Consequently, this externality-driven circumstance causes an excessive production level in the market, quantified as $(Q_1 - Q^*)$, along with an associated deadweight loss represented by the area labeled as E, as shown in **Table 2.1**.

Table 2.1 – Optimal quantity in the presence of externalities.

	Equilibrium (price=P_1)	**Social optimum (price=P^*)**	**Difference between social optimum and equilibrium**
Consumer surplus	A+B+C+D	A	-B-C-D
Private producer surplus	F+G+H+I+J	B+C+F+G+I+J	B+C-H
Cost of externality	E+C+D+G+H+J	C+G+J	E+D+H
Net social benefit	A+B+F+I-E	A+B+F+I	E
Deadweight loss	E	0	E

While acknowledging the presence of costs stemming from externalities (areas E+D+H), the overall net societal gains derived from chemical production remain positive. This remains true even when factoring in the cost of externality and consequently, the optimal level of pollution cannot be reduced to zero. This conclusion can be demonstrated using partial equilibrium analysis, as shown in **Fig. 2.3**, where two curves are depicted. The marginal net benefit curve (MNB) represents the variation in well-being due to a unit change in the quantity produced, while the marginal external cost (MEC) corresponds to the change in external costs resulting from a unit change in the quantity produced.

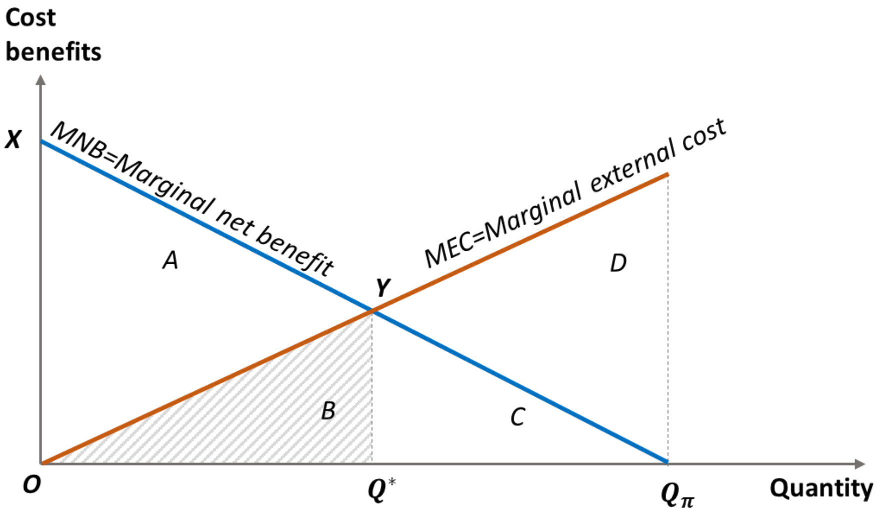


Fig. 2.3 – Optimal pollution level. Adapted from [14].

The MEC curve representing external costs, it is also related to the additional damage caused by the pollution generated to produce the marginal quantity Q_{n-th}. Hence the intersection of the MNB and MEC curves yields the optimal level of pollution:

$$MNB = MEC \tag{2.1}$$

However, the marginal net benefit is equal to the price P* minus the marginal private cost of production (MPC):

$$MNB = \mathrm{P}^* - MPC \tag{2.2}$$

Thus, substituting **Eq. (2.1)** in **Eq.(2.2)** and rearranging we obtain:

$$\mathrm{P}^* = MEC - MPC = MSC \tag{2.3}$$

Where the sum of marginal external costs and marginal production cost is equal to the marginal social cost (MSC), from which we deduce that the optimum is achieved when the price is equal to the marginal social cost.

2.4 Emission standards and fees

The discussion of *Section 2.3* shed light on the factors contributing to a market's inability to achieve efficiency in the presence of negative externalities. This logically leads to look for potential strategies capable of mitigating or eradicating these economic inefficiencies. One avenue worth exploring involves government intervention within the market structure, achieved by imposing acceptable pollution levels, commonly referred to as an "emissions standard".
Unfortunately, the task of establishing optimal emissions standards poses a considerable challenge for governmental bodies. Indeed, knowledge of the market demand curve, coupled with insights into the marginal private and social cost curves, is necessary. Additionally, a prerequisite for the operation of these standards, is that they must encompass an effective monitoring system capable of detecting instances when the polluting agent exceeds the limits and imposing a consequent fine.

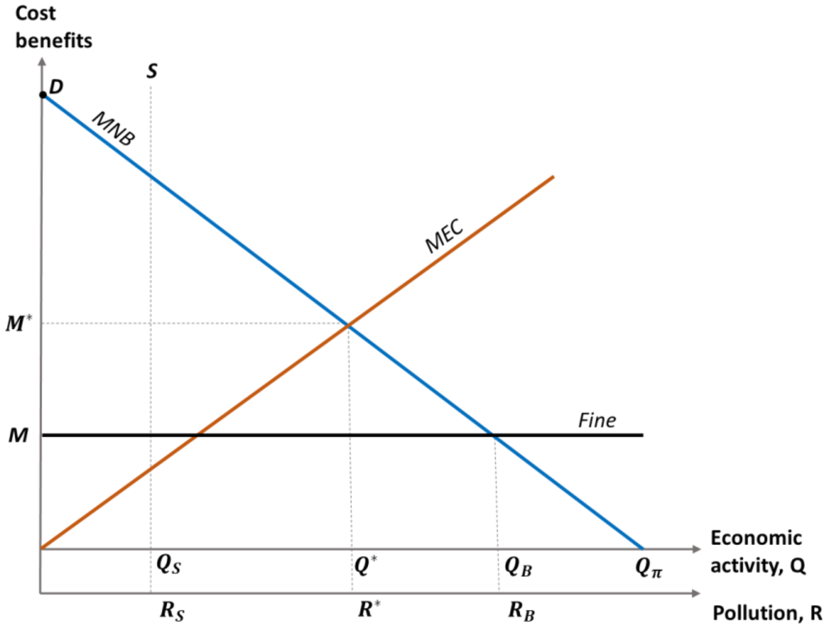


Fig. 2.4 – Possible inefficiencies of emission standards [14].

In **Fig. 2.4**, as in previous sections, MNB represents the change in net benefit resulting from a unit change in activity level. On the other hand, MEC denotes the marginal external cost, which indicates the value of the additional damage caused by pollution resulting from the quantity Q. Let's envision a fine established at level M and a standard set at level S. The optimal standard aligns with the previously determined optimal pollution level (Q^*). This type of environmental standards system needs an accurate identification of the socially optimal level and hence requires precise information.
Furthermore, the polluting agent is incentivized to pollute as long as the marginal benefits surpass the imposed fine; however, the fine is only paid if the polluting agent is subject to meticulous monitoring. This transition shifts from a deterministic scenario to a probabilistic one, where one must consider the probability of actually paying the fine. This probability can result in the polluting agent finding it advantageous to pollute beyond the socially optimal level.

Even in the case in which regulating authorities were capable of computing exactly the optimal emissions level for the entire market, they would still face the task of determining the admissible amount of pollution each individual firm can emit. Some firms will have the capacity to reduce emissions at lower costs compared to others. Deciding the socially optimal pollution allowance for each firm depends on the abatement expenses specific to each participant in the market.
If for example Firm A incurs in significantly higher costs than Firm B to lower pollution by a single unit, requiring Firm B to curtail its pollution would result in a lesser societal expense. The government can, to some extent, simplify the challenge of determining an efficient distribution of pollution rights by

enabling firms to trade emissions permits. Initially assigning rights to pollute and subsequently allowing firms to engage in permit trading within a competitive market can streamline the process. Firms with higher abatement costs will value more the privilege to emit one unit of pollution compared to those with lower abatement costs. The latter might even find it advantageous to exchange some of their pollution rights with firms confronting higher abatement costs. In a state of equilibrium, the distribution of pollution rights will be structured to minimize cumulative abatement costs.

2.4.1 Pigouvian taxes

In principle, the government can also mitigate the economic inefficiency arising from negative externalities through the implementation of a tax applied to the firm's production or to the quantity of pollutants emitted by the firm. This concept was first introduced by Arthur Cecil Pigou [15], according to whom, in the presence of harmful actions, it is necessary to establish a mechanism capable of internalizing external costs. This way, the acting entity considers the social costs stemming from its activity within its cost-benefit analysis. The solution would then entail finding a means to raise the costs for the firm, thereby reducing its production level to reach the socially optimal quantity through a tax imposed on each unit produced. By doing so, the firm's private cost curve would shift upwards, intersecting the marginal benefit curve (and the resulting equilibrium point) at a lower production quantity. The resolution would thus involve identifying a method to elevate the firm's expenses, consequently lowering its production level to align with the socially optimal quantity. This could be achieved through the imposition of a tax on each produced unit.

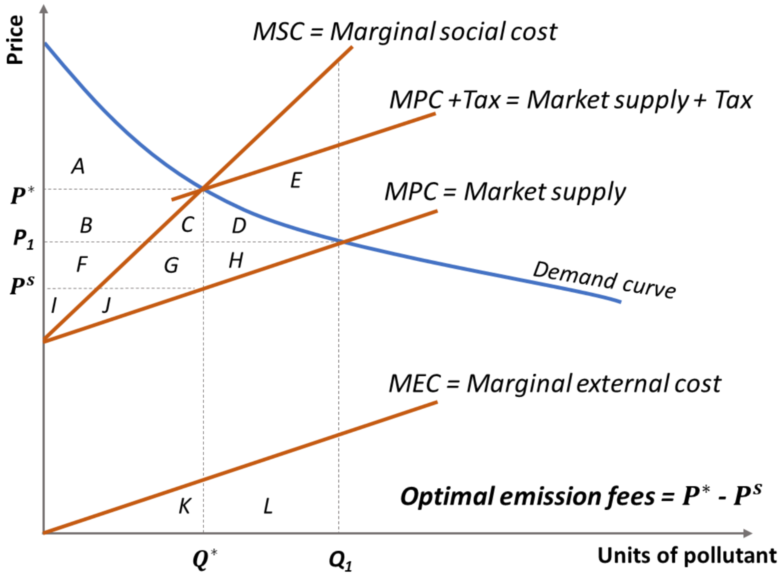


Fig. 2.5 – Optimal quantity in the presence of externalities. Adapted from [10].

An emissions fee represents a tax levied on pollution discharged into the surrounding environment. An optimized emissions fee will result in achieving the economically efficient output Q^*. Indeed, when an optimal fee is in place, the price paid by consumers must encompass not only the marginal private production cost but also the fee itself. The graph labelled "Market supply + Tax" illustrates the quantity that producers will make available for sale when the consumer price covers both the marginal private cost and the tax. At the point of optimal taxation, the demand curve intersects with the "Market supply + Tax" curve at the socially optimal quantity, Q^*. Consumers pay P^*, and producers receive a price equivalent to P^S. The government accumulates tax revenues of P^*- P^S corresponding to the areas B+C+F+G. This optimal tax configuration eradicates deadweight loss, as net benefits are as large as possible (A+B+F+I).

Table 2.2 – Optimal pollution fee with a negative externality.

	Equilibrium (with tax)
Consumer surplus	A
Private producer surplus	I+J
Cost of externality	C+ G+J
Government receipts from emissions tax	B+C+F+G
Net social benefit (consumer surplus + private producer surplus – cost of externality)	A+B+F+I

The tax precisely matches the marginal external cost stemming from pollution so that the marginal social benefit (P^*) equals the sum of marginal private cost (P^S) and marginal external cost (**Fig. 2.5**).
The same concept is illustrated in **Table 2.2**. Since consumer pay the price P^*, the consumer surplus is represented by the area A, the region beneath the demand curve and above P*. The private producer surplus encompasses areas I+J, which corresponds to the region below the price received by producers (P^S) and above the marginal private cost curve. External cost encompasses areas C+ G+J, equivalent to area K. The government receives tax revenues amounting to areas B+C+F+G. Net social benefits are the sum of consumer surplus, private producer surplus, tax receipts, and a deduction for external costs (area C+ G+J). This cumulative net benefit equates to areas A+B+F+I, mirroring the identical socially optimal net benefit demonstrated in **Fig. 2.2**.
Finding the exact amount of the Pigouvian tax in real-world cases is not straightforward. To do so, one would need precise knowledge of the values of all the curves depicted in **Fig. 2.5**, enabling the precise determination of the optimal quantity. Asymmetric information conditions may arise, leading to setting the tax either too low, resulting in continued pollution by firms, or too high, needlessly imposing an excessive and highly inefficient burden on polluters.

2.5 Property rights and the Coase theorem

Up until this point, we have explored the methods by which the government could address externalities through taxation (emissions fees and tolls) and regulatory mechanisms based on quantities (emissions standards). Coase et al. [16] demonstrated a fundamental theorem according to which the government has the option to solve the problem of externalities by allocating a property right, granting exclusive control over the utilization of an asset or resource, thereby avoiding interference from external parties.
According to Coase, market adjustments can occur naturally if property rights are appropriately allocated; therefore, achieving an optimal outcome is feasible regardless of whether the rights are granted to the party being polluted or the party causing pollution.

If property right are assigned to the polluted agent one could imagine that equilibrium point is found at zero pollution; however, as shown in **Fig. 2.6**, if the possibility of negotiating such rights and shifting to point *d* is considered, the polluter gains a net benefit equal to *oabd*, while the polluted agent incurs a cost equal to the area *ocd*. Indeed, through negotiation, the polluter could compensate the polluted agent with a greater quantity than the loss suffered, as the area *oabd* is larger than the area *ocd*. This holds true for all production levels from 0 to the optimal quantity Q^*, but not beyond it where polluter could not offset the damage since, for quantities above Q^* the MNB curve is below the MEC curve.
If on the other hand property rights are assigned to the polluting agent, one might assume that for the polluter holding property rights, the economically favorable position would involve maximum economic activity. However, let's consider an initial shift to point *h*: the polluted agent will negotiate with the polluter to reduce the level of activity, managing to offset this loss since the area $hefQ_\pi$ is greater than the area hgQ_π. The feasibility of negotiation will prove advantageous as long as the first area remains smaller than the second; thus, once again, a natural shift towards the socially optimal level occurs.

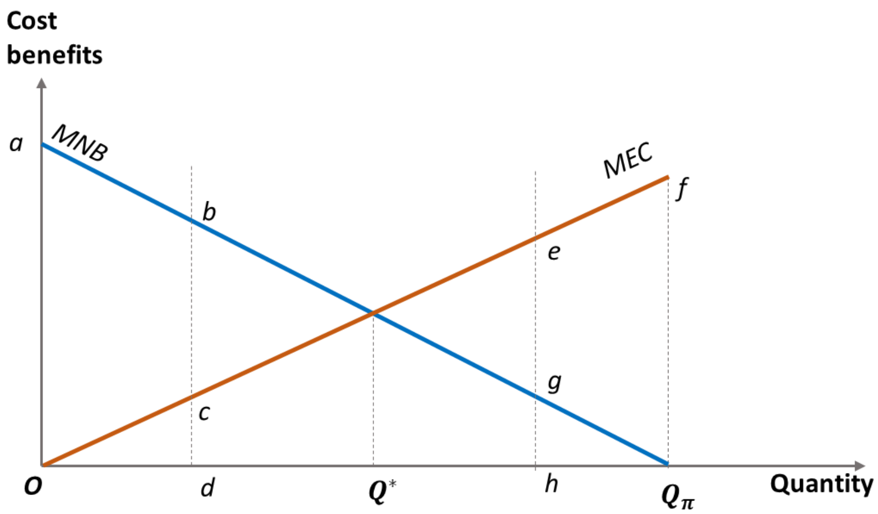


Fig. 2.6 – Optimal pollution level. Adapted from [14].

In [16], Coase exemplified this concept through a scenario featuring two farms. Farm A specializes in cattle farming, with its cattle occasionally wandering onto the property of a neighboring farm, Farm B, which primarily cultivates crops. The cattle from Farm A inadvertently create a negative externality by causing harm to the crops cultivated on Farm B and raises questions concerning weather the cattle should be left free to roam to onto the property of Farm B or if alternatively Farm B should demand that Farm A erects a fence to contain the cattle and who should pay for the fence.

The Coase Theorem posits that, irrespective of the initial assignment of property rights in the context of an externality, resource allocation becomes efficient when involved parties can engage in costless negotiation. If the owner of Farm A holds the right to allow their cattle to graze on the land of Farm B, the owner of Farm B will reimburse the owner of Farm A for the construction of a fence when the harm to Farm B's crops surpasses the fence's cost. Should the fence's cost exceed the crop damage, it becomes economically unfavorable for Farm B's owner to finance the fence, and the cattle will continue to roam freely. Essentially, this implies that when it is socially beneficial to erect the fence, it will indeed be constructed to rectify the externality.

Alternatively, let's consider the scenario where property rights are vested in Farm B, requiring Farm A to compensate Farm B for any incurred damage. In this setup, Farm A would decide to erect a fence when the harm inflicted upon Farm B's crops exceeds the cost of the fence. However, if the fence's cost surpasses the crop damage, Farm A will instead compensate Farm B for the damage incurred, leading once again to the cattle's uninhibited movement.

The example above illustrates a remarkable point of the Coase Theorem. Irrespective of whether the property rights are allocated to Farm A or Farm B, the resulting outcome remains unchanged and aligns with social efficiency. The construction of the fence takes place when the cost of the fence is lower than the harm inflicted on the crops, and conversely, the fence remains unconstructed when its cost exceeds the inflicted damage. However, although the Coase Theorem asserts that resource allocation will achieve economic efficiency regardless of the initial property rights assignment, the actual distribution of resources significantly depends on which of the parties possess the property rights. Indeed, If A owns the property rights, B pays for the fence. However, if B owns the rights, A pays for it.

Additionally, an important note concerns the fact that Coase Theorem assumes that bargaining is costless. If the bargaining process itself is costly (for example in the case in which If pollution harms thousands of people which may find it difficult to organize themselves to bargain about compensation), then the parties might not find it worthwhile to negotiate. Furthermore, in cases in which the parties lack knowledge about the costs and benefits associated with mitigating the externality, or when divergent viewpoints exist regarding these costs and benefits, the process of negotiation might not result in an optimal outcome. Additionally, both parties must demonstrate a willingness to engage in agreements that offer reciprocal advantages. Should one party decline to participate in negotiations or refuse to

provide an acceptable form of compensation to the other party, achieving an efficient allocation of resources might become an unattainable objective.
The Coase theorem presents other criticalities that make it impossible to reach the social optimum without external intervention. These include the need of perfect competition for the theorem to work and the fact that, given the extension over time of pollution related problems, it is complex to define which parties should be engaged in negotiation. The identification becomes even more intricate when referring to resources with open access, of which none holds ownership, making it extremely difficult to identify and allocate damages to the polluted agents, even in cases where negotiation takes place.
Finally, in the case of environmental externalities, the polluting agent is often also the polluted agent. Therefore, the marginal net benefit and marginal external cost curves upon which the negotiation is founded belong to the same individuals who might choose not to cooperate, opting to gain in the short term instead. These issues support the argument that market mechanisms alone are insufficient to achieve the social optimum, thereby rendering market failure inevitable without external intervention.

2.6 Tradable pollution rights

Apart from Coase's contributions, the works of Crocker [17] and Dales [18] are also often cited in relation to the development of emissions trading mechanisms. Additionally, Hardin [19] delved into the concept of "Tradable Pollution Rights."
In particular, Dales' approach [18] was grounded in the necessity to restrict open access to resources by assigning transferable property rights. He applied this concept in the context of watercourse pollution. In this scenario, a regulatory entity would set limits on the maximum allowable pollutant discharge over a specific time period. Transferable quotas would be allocated to polluters, where each quota corresponds to a defined quantity of pollutants that is permissible for discharge into the water.

This foundational concept laid the foundations for the greenhouse gas emissions trading system. The total permissible amount of GHG emissions is determined by a specific number of certificates established by a Public Authority based on the maximum acceptable pollution level in a given area.
Firms that manage to maintain emissions below the designated threshold can proceed to trade their surplus pollution allowances, thereby generating revenue through the sale of these quotas. Conversely, when pollution exceeds the quota allocation, companies are obligated to undergo financial outlays adhering to the "polluter pays" principle, as they must procure additional allowances to accommodate their emissions. Hence, polluting agents have the flexibility to engage in negotiations for a predetermined maximum level of these circulating permits.

The operational functioning of tradable pollution rights is shown in **Fig. 2.7**, where the MRC curve represents the marginal costs related to pollution reduction, while as previously, the MEC curve represents marginal external costs. The allocation of permits is under governmental regulation and is symbolized by curve S, characterized by its price independence. Conversely, the demand curve for permits follows the MRC curve. For instance, at price P_1, the permits demand is equal to Q_1 since when moving from Q_2 to Q_1 it is more convenient to reduce emissions compared to the purchase of permits when transitioning from Q_2 to Q_1. Hence, equilibrium at the socially optimal level of pollution is established through the equilibrium of permits supply and demand. Tradable permits introduce flexibility for polluting entities, benefitting those confronting high reduction costs, thus encouraging their engagement in permits acquisition from counterparts with lower abatement costs.

Consequently, a market for permits organically materializes as a platform designed to minimize expenditures in contrast to the conventional standard-oriented approach previously outlined. Another dimension of effectiveness lies in accommodating new market entrants. This framework gives the government the flexibility to adjust standards in tandem with shifts in negotiable permit demand, effectively positioning it as a permits bank, better addressing evolving market dynamics.

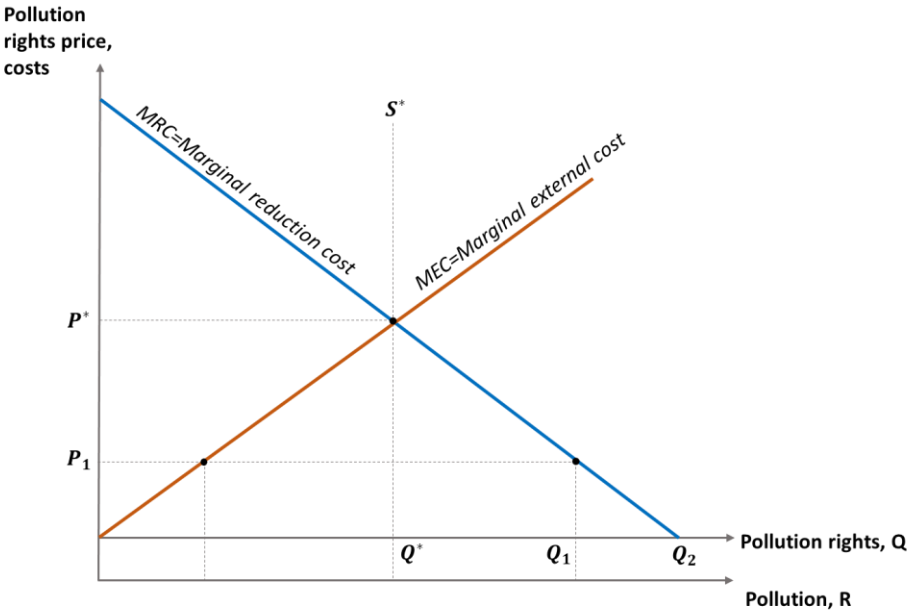


Fig. 2.7 – Optimal pollution level in the presence of tradable pollution rights. Adapted from [14].

Tradable pollution permits found their initial practical application in the United States in 1990, when under the "Clean Air" Act, the Environmental Protection Agency (EPA) specified limits on the number of pollutants allowed in the air anywhere the United States. Essentially, this system entailed allocating a certain number of pollution permits to businesses which could then be utilized or traded on the market by the respective enterprises. Since then, numerous tools have been implemented to mitigate greenhouse gas emissions and pollution levels. *Chapter 3* provides an overview of these instruments, with a specific emphasis on the European Emission Trading System (EU-ETS).

2.7 Conclusions

The lenses of microeconomics can be a valuable tool to examine the challenging problem of climate change and the financial barriers hindering greenhouse gas emissions reduction.
Partial equilibrium analysis applied to competitive markets, illustrates that at equilibrium, perfectly competitive markets efficiently allocate resources. However, markets are in reality not perfectly competitive, and externalities exist, both positive and negative (like pollution), disrupting market efficiency.

Various methods to address negative externalities stemming from pollution have been proposed, including emission standards, Pigouvian taxes, and tradable pollution rights. The Coase theorem, illustrates how property rights allocation and negotiation can drive optimal resource allocation, albeit with limitations. In this context, tradable pollution rights, represent an extremely powerful tool.
Emissions quotas are defined and firms that manage to maintain emissions below the designated threshold can proceed to trade their surplus pollution allowances, thereby generating revenue through the sale of these quotas. Conversely, firms that exceed their quota allocation must procure additional allowances to accommodate their emissions. This enables cost-effective emissions reduction by incentivizing emissions cutting where it is more convenient from a societal perspective.

Chapter 3

Emission Trading Systems

International climate regulations have played a fundamental role in reducing greenhouse gas emissions. The Kyoto Protocol and the Paris agreement laid the foundations for flexible mechanisms, rooted in the economic principle of cost-effectiveness, that opened the way to the creation of Emission trading systems (ETS). ETS typologies include Cap and Trade and Baseline and Credit systems. Moreover, carbon markets can be divided into mandatory regulated markets and voluntary carbon offset markets.
This chapter analyses the use of these regulatory frameworks in promoting sustainable global climate actions and setting the stage for collaborative efforts in emissions reduction and environmental protection.

3.1 Introduction

To address issues related to climate change, governments can employ carbon emissions taxes in conjunction with other tools such as research and development, sector-specific regulations, investments in technologies and infrastructure, removal of regulatory barriers, and market reforms, among others. Tools for carbon pricing can be broadly categorized into two main groups: direct carbon pricing and indirect carbon pricing.

Direct carbon pricing entails applying a proportional cost to emissions generated by a product or activity through a carbon tax or emissions trading system (ETS). By imposing a uniform price per ton of CO_2 across multiple sources, direct pricing ensures consistent abatement costs and directs investments toward economically advantageous technological applications.

On the other hand, indirect carbon pricing refers to methods that alter the prices of products associated with carbon emissions in ways that are not directly proportional to those emissions. Examples of indirect carbon pricing include fuel and raw material taxes, as well as fuel subsidies that impact energy markets. This is the case with some excise taxes, i.e., legislated intranational taxes on specific goods or services at the time they are purchased [20]. Fuel excise taxes for instance impose a flat tax per liter of gasoline, indirectly incorporating a price on carbon emissions resulting from its combustion.

Direct carbon pricing systems (including carbon taxes and ETS) have predominantly been implemented in high- to middle-income countries thus far. In contrast, indirect carbon pricing systems, such as fuel excise systems, are more commonly adopted in many developing countries. This discrepancy partly arises from the complexity of direct pricing, especially for countries that have not previously embraced such measures, while on the other hand most countries already have built significant experience in introducing fuel excise taxes and gradually eliminating fuel and raw material subsidies over the course of decades. *Section 3.2* presents a review of the current status of direct taxation systems in the world, while *Section 3.5* present a focus on the European ETS.

3.2 Current status of direct taxation systems

An examination of direct taxation systems reveals considerable complexity. As of April 2022, there were 68 carbon pricing initiatives (CPIs) in operation, comprising 36 carbon taxes and 32 ETS implementations, as shown in **Fig. 3.1**.

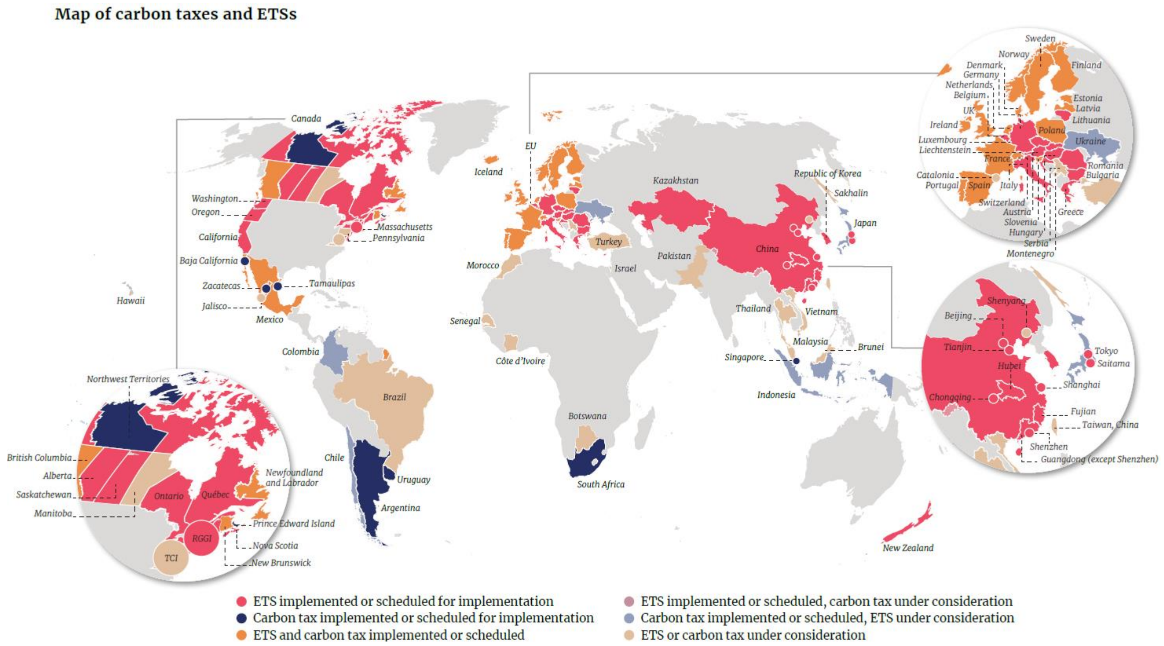
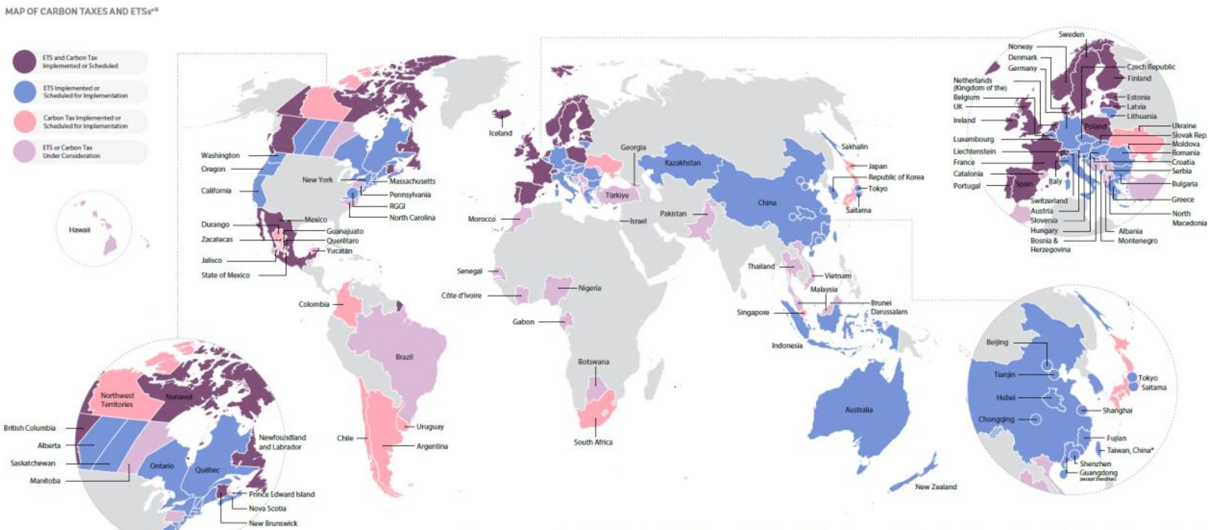


Fig. 3.1 – Map of carbon taxes and ETSs as of April 2022 [21].

As of April 2023, the number of carbon taxes or ETS implemented had increased to 73, as shown in **Fig. 3.2**, showing that the carbon pricing landscape is experiencing rapid change.



(xiii) Instruments are considered "scheduled for implementation" once they have been formally adopted through legislation and have an official, planned start date. Instruments are considered "under consideration" if the government has announced its intention to work toward the implementation of a carbon pricing initiative and this has been formally confirmed by official government sources. Some countries that have mechanisms implemented also have additional instruments under consideration. For subnational jurisdictions only the subnational instrument is reflected.

Fig. 3.2 – Map of carbon taxes and ETSs as of April 2023 [22].

Indeed, in recent years, the carbon pricing landscape has witnessed several noteworthy developments. In January 2022, Uruguay initiated a new carbon tax, while three new ETSs were launched within subnational regions in North America, specifically Oregon, New Brunswick, and Ontario [21]. In 2022, a new ETSs commenced in Austria and the state of Washington in the United States, while Indonesia announced the launch of a mandatory national ETS. At the subnational level, three new carbon taxes were implemented in states within Mexico, in Querétaro, in the State of Mexico, and in Yucatán, while a fourth carbon tax in Guanajuato is set to into force in June 2023 [22].

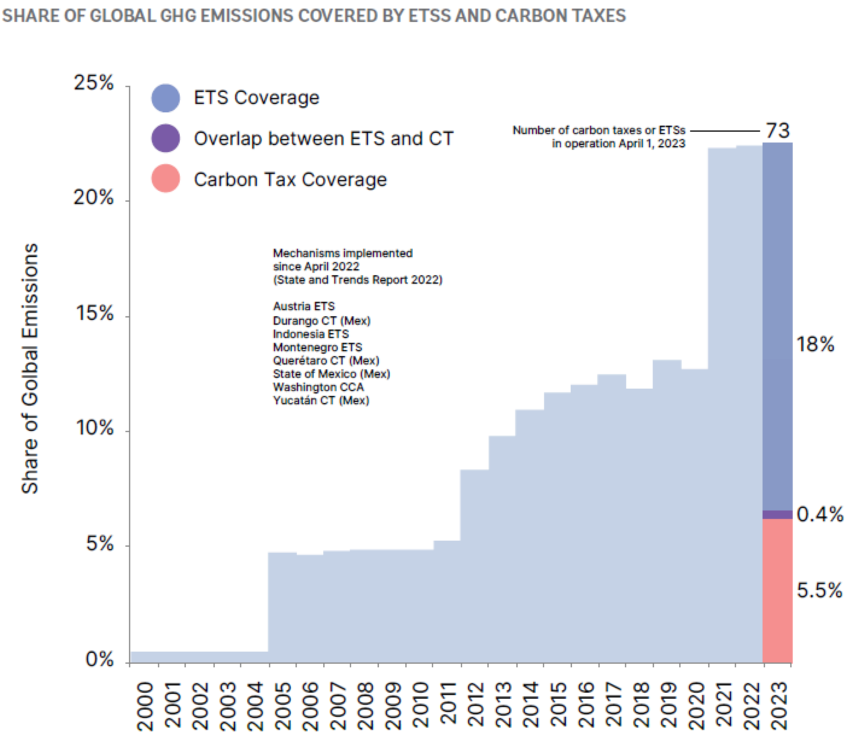


Fig. 3.3 – Share of global GHG emissions covered by carbon pricing instruments [22].

Presently, about 23% of the total GHG emissions are encompassed by operational CPIs, as depicted in **Fig. 3.3**, an increase of less than 1% compared to 2022 and mirroring the value observed in 2021. While there has been a relatively moderate increase in the number of new CPIs introduced since 2020, several other countries are proactively stepping into the arena. Israel, Malaysia, and Botswana have made public their intent to establish new CPIs, each tailored to their unique contexts. Additionally, Vietnam has outlined its strategic steps towards the establishment of an ETS. Beyond these specific instances, a range of other jurisdictions across Africa, Central Europe, and Asia are actively engaged in assessing the feasibility and potential benefits of implementing their own Carbon Pricing Initiatives. This collective momentum shows an increasing recognition of the efficacy of carbon pricing as a tool to address environmental issues while also promoting sustainable economic growth.

In absolute terms, China currently represents the largest carbon market through its Emissions Trading System. In 2021, China's national ETS extended its reach to encompass more than 2,100 power plants, collectively responsible for approximately 4.5 billion tons of CO_2 equivalent emissions annually, corresponding to over 30% of China's total GHG emissions, as shown in **Fig. 3.4**. In contrast to other pricing mechanisms, the pricing of emission allowances within this context remained relatively low, averaging around \$8-10 per ton of CO_2 during 2021-2022. The year 2021 marked a milestone with the exchange of a cumulative total of 179 million tons of CO_2 equivalent emission allowances, generating a substantial cumulative revenue of nearly 7.7 billion yuan (\$1.2 billion).

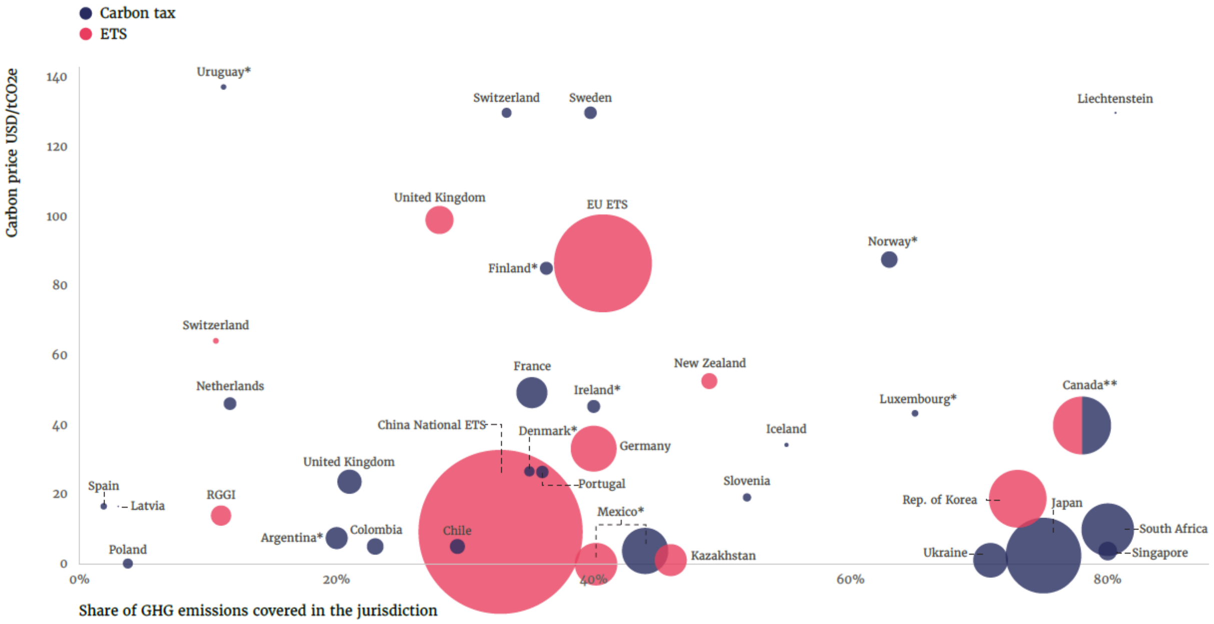


Fig. 3.4 – Absolute emissions coverage, share of emissions covered, and prices for CPIs across jurisdictions [21]. Bubble size represents absolute covered total GHG emissions.

On the other hand, the European Union constitutes the largest carbon market in terms of traded value. The EU Emissions Trading System (EU ETS) has witnessed record trading activity and prices both in spot and futures markets. Over 15 billion emission allowances were exchanged on the Intercontinental Exchange, the largest secondary market platform for EU allowances. The EU's climate law came into effect in July 2021, setting a binding climate target for the entire Union: a 55% reduction in GHG emissions by 2030 compared to 1990 levels and achieving net-zero emissions by 2050. The new commitment, known as "Fit for 55" [23], includes the addition of a new ETS covering the transport and buildings sectors. This runs alongside the current EU ETS, which covers energy, industry, and aviation sectors. The proposed package aims to expand the existing EU ETS system to include maritime transport emissions starting from 2023 and encompass 100% of emissions for intra-EU voyages and 50% for voyages between EU ports and, by 2026, ports of third countries. The potential carbon-derived revenues from the maritime sector are considered substantial, with estimates reaching \$40-60 billion annually by 2050. Therefore, the strategic utilization of these carbon-derived revenues could become crucial in accelerating the decarbonization of maritime transport and ensuring an equitable transition to carbon-neutral maritime transport among nations.

The record levels of direct carbon pricing witnessed in various jurisdictions in 2021 can be attributed to a combination of policy decisions, broader economic trends, with global energy prices playing a pivotal role and increased speculation. Indeed, numerous markets, including the linked EU-Swiss and California-Québec systems, allow emissions allowance trading for nonparticipants, potentially enhancing liquidity and price clarity. However, this expansion introduces manipulation risks. Nonparticipants include brokers, traders, and banks that assist ETS-covered firms with risk mitigation. Moreover, investors seeking credits for future value growth or portfolio diversification, driven by uncertainties in traditional inflation hedges, now enter the market. EU legislators have indicated their intent to tackle potential manipulation through forthcoming ETS reforms, and some have even suggested the prospect of confining trading to include only participants and authorized representatives.

Price peaks were observed in multiple systems, predominantly within advanced economies' ETS (as shown in **Fig. 3.5**). Record prices were recorded in linked ETS markets of the EU and Switzerland, linked markets of California and Quebec, and the New Zealand ETS. However, in most jurisdictions, prices still remain below the levels required to achieve the goals of the Paris Agreement estimated around 100 $/tCO_2$ equivalent [24].

Additionally, sharp price drops were recorded in several systems in early 2022, though prices have since begun to recover. Prices in the EU ETS, the New Zealand ETS, the UK ETS, and the Republic of Korea ETS saw dramatic falls following the invasion of Ukraine in February. Prices in all four systems have since begun to recover but they remain below the heights recorded before the war.

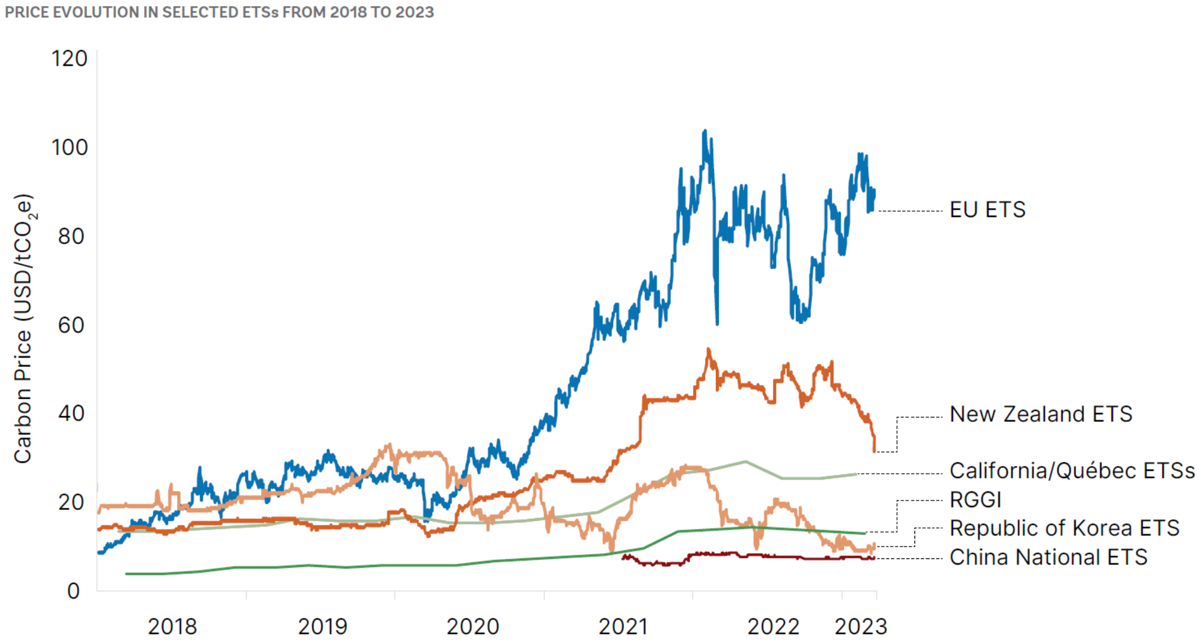


Fig. 3.5 – Price evolution in select ETSs from 2018 to 2021 [22]. Based on data from [25].

Several jurisdictions have nevertheless established more ambitious price trajectories (**Fig. 3.6**). For instance, Singapore has proposed a gradual increase in the carbon tax rate (currently 5 SGD), reaching 25 SGD (18 USD) per tCO_2eq by 2024 and 2025, further elevating it to 45 SGD (33 USD) per tCO_2eq by 2026 and 2027, with an ultimate target of 50-80 SGD (37-59 USD) per tCO2eq by 2030. Similarly, the South African government has unveiled a proposal to raise the carbon tax rate from its current level, just below 10 USD per tCO_2eq, aiming to achieve 20 USD per tCO_2eq by 2026, 30 USD per tCO_2eq by 2030, and 120 USD per tCO_2eq beyond 2050. These escalations follow last year's announcement by Canada to annually increase its carbon minimum prices by 15 CAD (12 USD) per tCO_2eq, aiming to surpass 170 CAD (136 USD) per tCO_2eq by 2030.

However, response to the surge in energy commodity prices, worsened by the Ukraine conflict, could influence the timelines for carbon tax rate increases. As of April 2022, Indonesia has declared a postponement of carbon tax introduction due to the economic impact of soaring energy prices and Mexico has announced exemptions for carbon tax on gasoline and diesel due to market conditions.

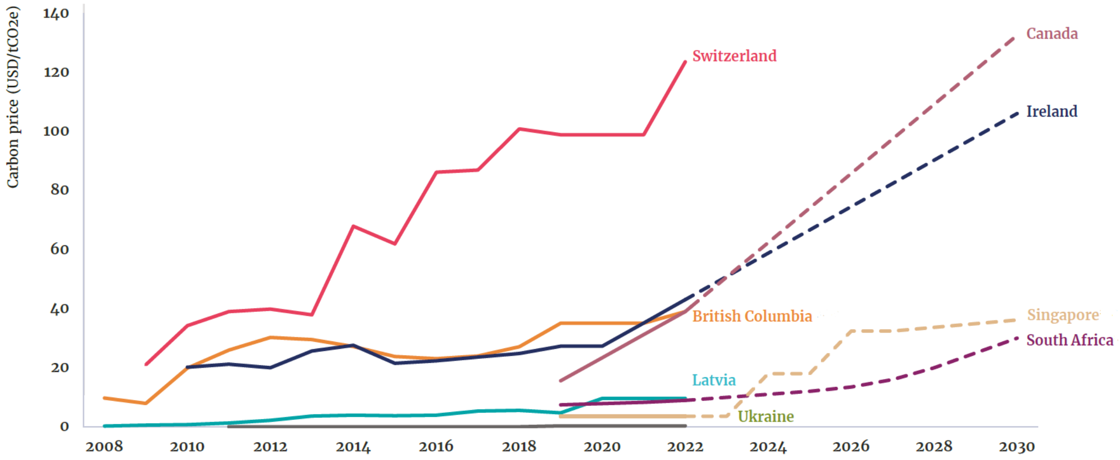


Fig. 3.6 – Carbon tax rates in six jurisdictions and expected price evolution [21].

3.3 International climate change regulations

Understanding of the context in which an ETS operates, of the international climate change regulations, is essential to deeply understand the system. In this context, it is worth delving into the historical evolution of climate agreements, notably the Kyoto Protocol and the Paris Agreement (outlined in the following), to appreciate the foundations upon which ETSs have evolved.

The Kyoto Protocol

The efforts to address the rising climate-altering emissions and global warming can be traced back to 1992, during the inaugural United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro [26]. During this conference, 154 countries signed an international environmental treaty with the aim of raising awareness among governments about the need to reduce greenhouse gas emissions. However, the treaty did not impose any mandatory targets.
It was in 1997, during the third Conference of the Parties (COP3) held in the Japanese city of Kyoto, that the governments of industrialized countries decided to opt for a more stringent agreement by signing the document that would later become known as the "Kyoto Protocol" [27]. In force since February 2005, the Kyoto Protocol has been the first international agreement imposing binding targets for GHG emissions. Under this Protocol, a group of 37 industrialized nations along with the European Union pledged to reduce their emissions by an average of 5% relative to 1990 levels, during the period from 2008 to 2012. Each participating country committed to achieving its unique emissions reduction target (the EU aimed for a reduction of 8%, Japan targeted a 6% reduction, while Australia set a target of increasing emissions by 8%, etc., [28]). These targets were established through a collaborative negotiation process rather than being determined unilaterally. The characterization of the Kyoto Protocol as a top-down regulatory framework primarily stems from this negotiated approach, where the precise allocation of emission reduction efforts was agreed upon collectively from the outset.
The objective of the Kyoto protocol was to contrast global warming by reducing emissions of six greenhouse gases resulting from human activities: carbon dioxide, hydrofluorocarbons, perfluorocarbons, methane, nitrous oxide, and sulfur hexafluoride. To implement the Kyoto Protocol, while at the same time granting participating countries a certain degree of freedom in meeting their

commitments, flexible mechanisms were introduced: International Emissions Trading (IET), the Clean Development Mechanism (CDM), and Joint Implementation (JI) [29]:

- **International Emission Trading (IET)**: Envisaged in Article 3 of the Protocol, IET facilitated the exchange of Assigned Amount Units (AAUs) among countries with emission reduction targets, often referred to as Annex-B countries. This allowed countries that exceeded their targets to trade surplus AAUs.

- **Clean Development Mechanism (CDM)**: Outlined in Article 12 of the Protocol, CDM permits industrialized and transition economies to implement projects in developing countries (belonging to the non-annex I group) that yield environmental benefits through reduced greenhouse gas emissions while fostering economic and social development in the host countries. Simultaneously, these projects generate emission credits known as Certified Emission Reductions (CERs) for the sponsoring countries.

- **Joint Implementation (JI)**: Specified in Article 6 of the agreement, JI encompassed similar projects in developed countries, particularly in transition economies. The resulting credits obtained, referred to as Emission Reduction Units (ERUs), could be used jointly with the project host country.

These mechanisms were rooted in the economic principle of cost-effectiveness and shared the overarching goal of reducing emissions where it is most cost-efficient, and these credits became the tradable units within the framework of the Kyoto Protocol [29].
While built upon strong principles, the Kyoto Protocol faced a significant limitation in the relatively small portion of global emissions subject to reduction targets. In fact, the 36 countries that committed to emission reductions accounted for just 24% of global emissions in 2010 [30].
For this reason, from the moment the Kyoto Protocol came into effect, the question of what to do after 2012, when the Kyoto emission targets expired, became pressing. Starting with COP15 (Copenhagen, 2009), successive annual COP meetings sought to address this issue. The EU leaned toward establishing a new framework similar to Kyoto, but one that also included emission targets for developing countries. However, convincing all parties to accept this proposal was challenging. After COP15, international climate negotiations pivoted toward a bottom-up approach. This shift gained momentum at COP16 in Cancun and COP17 in Durban, culminating in plans for a post-2020 climate agreement reached in 2015 COP21 in Paris. In the meantime, the Kyoto's Protocol's second commitment period (2013-2020) acted as a bridge to the post 2020 regime, although countries that took new emission reduction targets for that period collectively only accounted for less than 15% of global emissions.

The Paris agreement

The Paris Agreement, which came into force in 2016, established the goal of limiting the global temperature increase to 2 °C above pre-industrial levels and of actively pursuing efforts to limit it to 1.5 °C. Signed by 195 counties accounting for 99% of global GHG emissions, central feature of the Paris Agreement is the fact that each country's contribution is determined unilaterally. However, contrary to the Kyoto Protocol, the Paris agreement obliges all countries to take action to limit global warming. Countries voluntary commitments (or formal pledges), called nationally determined contributions (NDC), can be heterogeneous in nature, but once formulated are binding and subject to monitoring and reporting duties [31].

The agreement contains the provision for countries to employ cooperative approaches (Article 6) to meet NDCs and enhance climate ambition. This aims to reduce global mitigation costs by over 50%.
Although they differ in some important respects, the cooperative approaches within the Paris Agreement are direct successors to the flexible mechanisms of the Kyoto Protocol. Article 6 of the Paris Agreement describes them with a somewhat vague formulation, leaving room for interpretation over the past years.

Fundamental issues related to the scope, governance, accounting, and infrastructure of these cooperative approaches have been subject to lengthy negotiations. Article 6 of the Paris Agreement comprises four main parts [29]:

- **Article 6.1** includes a general provision for international cooperation concerning countries' NDCs and encompasses all specific cooperation cases under Article 6 and potential future ones.

- **Articles 6.2 and 6.3** contain provisions enabling Parties to cooperate through 'Internationally Transferred Mitigation Outcomes' (ITMOs). These articles specify the steps Parties must take to use ITMOs in relation to their NDCs. The Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA), responsible for overseeing the agreement's implementation, is limited to providing guidance and develop accounting principles that all Parties engaged in ITMOs should adhere to [32].

- **Articles 6.4 to 6.7** contain provisions outlining a multi-scope mechanism to generate emission reductions that can be used to fulfil another Party's NDC and support sustainable development. Unlike Article 6.2, this mechanism operates under the authority and guidance of CMA. CMA is responsible for setting standards in all aspects, including approval processes, technical aspects regarding the quality and quantity of transfers, and preventing double counting.

- **Articles 6.8 and 6.9** establish a framework for non-market-based cooperative approaches.

The two mechanisms outlined in Articles 6.2–6.3 and Articles 6.4–6.7 allow international emissions trading. Article 6.2 establishes a framework that permits international connections between Emissions Trading Systems (ETSs) or even between various market-based mechanisms. It also provides room for the exploration of more innovative concepts. In contrast, Article 6.4 presents a robust yet somewhat more restrictive approach, aiming to establish an enhanced successor to the Kyoto Protocol's Clean Development Mechanism (CDM) and Joint Implementation (JI) initiatives [33].

Subsequent COPs have contributed, with progress and challenges, to advancing the global climate agenda. Notably, COP26 (Glasgow 2021) produced several significant outcomes. Efforts have focused on defining new ambitious national commitments to reduce emissions by 2030 and mobilizing financing for developing countries. COP26 also adopted an agreement on methane emissions reduction and made strides in addressing deforestation and forest conservation.
The latest COP held in Sharm el-Sheikh (COP 27) did not bring about significant upheavals, but concluded with an important breakthrough, the adoption of a Loss & Damage Fund for vulnerable countries hit hard by climate disasters opening new avenues for multilateral cooperation.

3.4 Types of carbon offset markets

Carbon offset markets can broadly be grouped into mandatory and voluntary programs and Cap and Trade systems or Baseline and Credit systems. These concepts are briefly discussed in this section, outlining the main differences between these systems.

ETS typologies: “Cap and Trade” and “Baseline and Credit” systems

A tradable permit system can be characterized by two primary approaches: the Cap-and-Trade system and the Baseline and Credit system.
In a **Cap-and-Trade system**, a maximum emissions limit is established, and emission permits are either auctioned or distributed for free based on specific criteria. Each pollutant is then assigned a fixed number of transferable emission permits, authorizing them to emit into the atmosphere an amount equivalent to the rights they hold. Essentially, this creates allowances, which are equivalent to the right to emit

greenhouse gases equivalent to 1 tCO_2eq. Each year, a portion of these allowances is allocated for free to certain participants, particularly in sectors where there is a risk of relocation (i.e., Carbon Leakage, see *Section 3.6*), while the rest is typically sold through auctions. At the end of the year, participants must surrender an allowance for every tCO_2eq emitted during that year. If a participant has insufficient allowance (because measures taken to reduce their emissions were insufficient) they must purchase additional allowances in the market to comply with regulations. Participants can buy allowances at auctions or from each other. If they use fewer permits than they possess, they can enter the market as sellers.

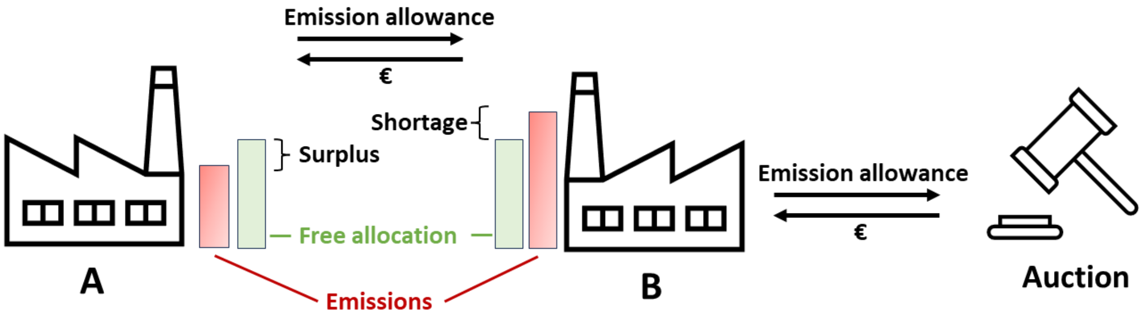


Fig. 3.7 – Cap and Trade emission trading scheme. Adapted from [34].

In the example depicted in **Fig. 3.7**, Plant B does not possess enough free allowances to cover its emissions, so it can comply with the limit imposed by the legislation by purchasing allowances from Plant A or through auctions. Participants can also choose to bank allowances for use in subsequent years. Allowances hold value because there is a limited supply, and there is demand for these allowances from participants for whom the cost of reductions is higher than for others.
Compliance is ensured through a penalty and enforcement framework. Significant fines are imposed if businesses fail to return an adequate number of allowances on time. For instance, in the case of the EU Emissions Trading System (EU-ETS), fines are set at 100 €/ tCO_2eq and increase with EU inflation from 2013 [34].

On the other hand, in a **Baseline and Credit system**, there is no fixed limit on emissions, but polluters who reduce their emissions more than what is otherwise required can earn credits that they can sell to others in need of compliance. Any reduction below the individually imposed baseline level offers the opportunity to obtain emission credits, which can be used to fulfill the obligation for the following years or simply sold to other companies with higher emissions compared to the baseline.

In general, it is recommended that permits or emission allowances in cap-and-trade systems be auctioned rather than distributed for free ("grandfathered"). Auctions ensure that the revenues related to environmental policies go to public authorities rather than being captured by existing polluters. However, in practice, most permits have been distributed for free so far. On the other hand, when environmental taxes are used, they often include some differentiation in tax rates among polluters.
The current use of emission trading systems is documented in a database freely available on the OECD website [35]. This database provides information on environmental issues addressed by the trading system, the traded item, trading partners, any revenues generated from permit sales, and more.

With *Baseline and credit systems*, it can be challenging to verify the extent to which emission reductions are "additional," meaning they represent something different from what would have occurred anyway. On the other hand, one concern with a *Cap-and-Trade system* and other types of emission limiting systems, is that when they are combined with other tools, such as various subsidy scheme, there is a risk that the additional tools may only incur additional costs without providing further benefits. These issues are discussed extensively in [36].

The European Union has opted for a *Cap-and-Trade* structure as the mean to achieve its GHG reduction target. The flexibility of *Cap-and-Trade system*, combined with other key advantages, played a significant role in choosing this structure:

- *Quantity certainty*: GHG emission trading directly limits emissions by setting a system cap designed to ensure compliance with relevant commitments. There is certainty about the maximum quantity of greenhouse gas emissions for the period during which system limits are set. This is crucial to support EU international objectives and environmental goals.

- *Cost-effectiveness*: Trading allows reaching the exact carbon price needed to achieve the desired goal. The flexibility trading brings means that all businesses face the same carbon price, ensuring emissions are reduced where it's most cost-effective to do so.

- *Revenues*: If greenhouse gas emission allowances are auctioned, it creates a source of income for governments, which should be used at least in part to finance climate change mitigation measures in the EU or other member states

- *Minimizing risks to member state budgets*: The EU ETS provides certainty for emission reductions in plants responsible for approximately 50% of EU emissions. This reduces the risk that member states will need to purchase additional international units to meet international commitments under the Kyoto Protocol.

Mandatory schemes and voluntary programs

There are essentially two categories of Carbon Offset Markets where emission credits are traded: *regulated markets*, which are established and overseen by regional, national, and international carbon reduction programs, and *voluntary markets*, which enable businesses or individuals to purchase emission reduction certificates on a voluntary basis. Regulated markets are generally characterized by a big size, while voluntary markets are typically characterized by smaller sizes.

Cap and trade schemes typically fall within the regulated market category, with participants identified by governments based on factors such as carbon intensity, sector, or business size.

In contrast, baseline-and-credit mechanisms primarily operate within the voluntary market sphere and have generally evolved in response to the demand from organizations seeking to manage their carbon footprint independently. Voluntary markets function autonomously from compliance markets, and the emission credits traded within them cannot be used to fulfill the legal and regulatory obligations imposed on organizations by compliance markets.

3.5 The EU-ETS

The European Union Emission Trading Scheme (EU-ETS) represents a cornerstone of the EU's strategy to combat climate change and is an essential tool for economically efficient greenhouse gas (GHG) emission reduction. Established in 2005 under the framework established by the Kyoto Protocol, the EU ETS is the world's first and largest international emissions trading system, spanning across 31 countries, including the 28 EU member states, Iceland, Liechtenstein, and Norway. This market operates on the cap-and-trade principle and relies heavily on the flexibility mechanisms mentioned earlier. The system places limits on emissions from over 11,000 high-energy-consuming facilities and airlines operating within the European Economic Area (EEA), accounting for approximately 45% of the EU's total GHG emissions [37]. Additionally, a new separate emissions trading system was created in 2023, commonly referred to as ‘ETS2’ [38]. The ETS 2 covers fuel combustion in buildings, road transport and additional sectors, mainly small industry not covered by the existing EU ETS.

From its inception, the EU ETS was designed to be part of the emerging global carbon market, contributing to its development. The significance of the EU-ETS in terms of market volume and demand

has led its price to become the benchmark for the international carbon market. In practical terms, the EU ETS is linked to the Kyoto Protocol through a community directive, allowing regulated facility owners to use internationally generated emission credits to meet a portion of their compliance obligations.
Since its inception, the EU ETS has undergone numerous changes and is divided into distinct trading periods, known as 'phases,' comprising four phases spanning from 2005 to 2030.

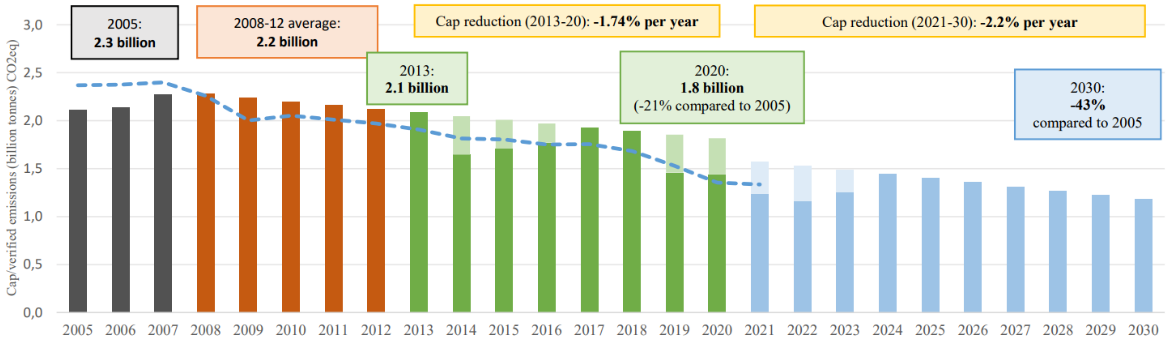


Fig. 3.8 – Emissions cap set in the EU ETS, compared with verified emissions. Legend: bars (cap), light shade bars in 2014-16 (allowances backloaded in phase 3), light shade bars since 2019 (feeds of allowances to the Market Stability Reserve), dash line (verified emissions) [39].

Phase 1 (2005-2007)

The initial phase of the European Union Emissions Trading Scheme (EU ETS), which took place from 2005 to 2007, served as a pilot phase. Its primary objectives were to evaluate price formation in the carbon market and to establish the essential infrastructure for monitoring, reporting, and verifying emissions. In Phase 1, businesses were restricted to using units generated under the Clean Development Mechanism (CDM) for compliance with the EU ETS. The main goal of this phase was to ensure the effective functioning of the EU ETS system before 2008, enabling EU member states to meet their commitments under the Kyoto Protocol. The Linking Directive allowed enterprises to use emission reduction units generated through mechanisms under the Kyoto Protocol, such as the Clean Development Mechanism (CDM) and Joint Implementation (JI). Key features of Phase 1 included:

- Coverage of CO_2 emissions solely from power generators and energy-intensive industries.
- Allocation of nearly all allowances to businesses free of charge.
- A fine of 40 €/ tCO_2eq for non-compliance.

Due to the absence of reliable emissions data, the caps in Phase 1 were established based on estimates. Consequently, the total number of allowances issued exceeded actual emissions, leading to an oversupply. As a result, in 2007, the price of allowances plummeted to zero. According to the annual reports on the carbon market by the World Bank, during Phase 1, trading volumes increased from 321 million allowances in 2005 to 1.1 billion in 2006 and 2.1 billion in 2007 [40], as shown in **Fig. 3.8**.

Phase 2 (2008-2012)

The second phase of the EU Emissions Trading Scheme (EU ETS) took place from 2008 to 2012, coinciding with the initial commitment period under the Kyoto Protocol. Starting in 2008, businesses were also allowed to use emission reduction units generated under the Joint Implementation (JI) to fulfill their obligations within the EU ETS. This development made the EU ETS the largest source of demand for Clean Development Mechanism (CDM) and JI emission reduction units. In 2012, the scope of the EU ETS was expanded to include aviation related emissions. Key features of Phase 2 included [40]:

- A lower limit on allowances (approximately 6.5% less than in 2005).
- The addition of three new countries: Iceland, Liechtenstein, and Norway.
- Inclusion of nitrous oxide emissions from nitric acid production in several countries.
- A slight decrease in the allocation of free allowances to about 90%.
- An increase in the non-compliance penalty to 100 €/ tCO_2eq.
- Businesses were able to purchase international credits, totaling around 1.4 billion tCO_2eq.

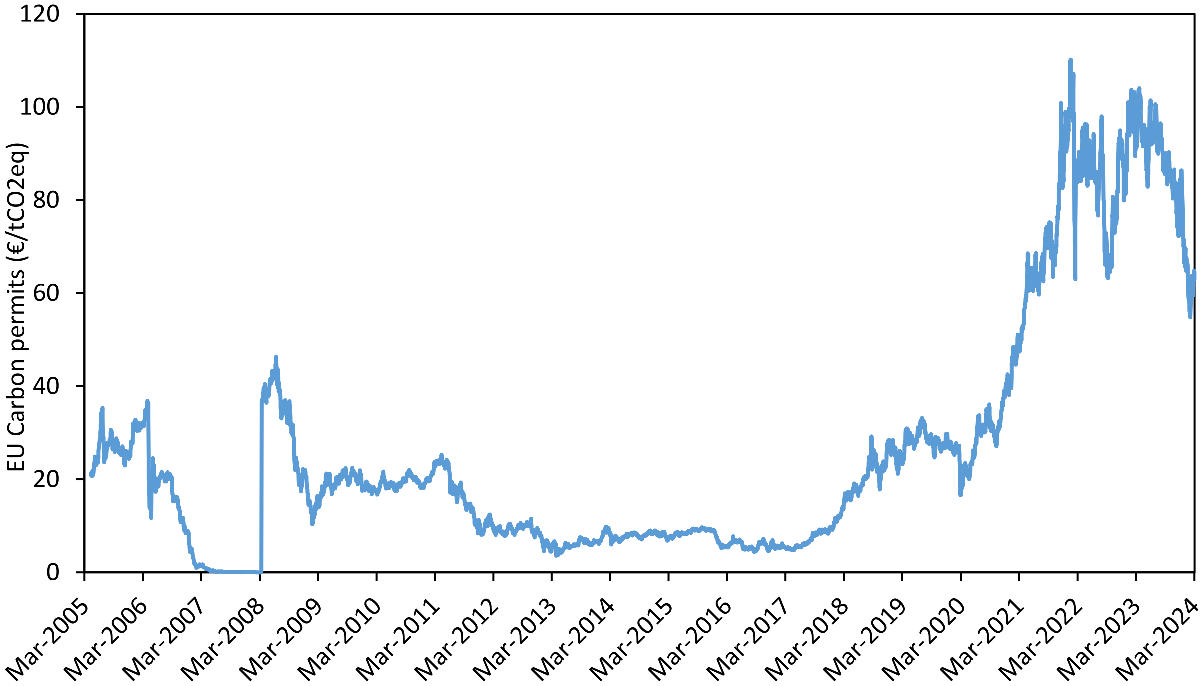


Fig. 3.9 – Price of EU ETS allowances 2005–2023. Source: Bloomberg.

As verified emission data from the pilot phase became available, the cap on allowances was reduced in Phase 2 based on actual emissions. However, the economic crisis of 2008 led to greater emission reductions than anticipated, which put significant downward pressure on carbon prices.

During Phase 2, the EU ETS became the primary international carbon market. For instance, in 2010, EU allowances accounted for 84% of the total global carbon market value, with trading volumes increasing from 2.3 billion in 2008 to 5.4 billion in 2009 and 7.9 billion in 2012 according to data from Bloomberg New Energy Finance.

Phase 3 (2013-2020)

The third phase of the EU ETS benefitted from the lessons learned in the preceding two phases. Extensive efforts were made to harmonize the scheme throughout the European Union following a review of the EU ETS, which was agreed upon in 2008. This third phase spanned from 2013 to 2020, coinciding with the second commitment period of the Kyoto Protocol. Key features of this phase included [40]:

- A unified emissions cap for the entire EU, replacing the previous system of national caps.
- An extended duration of 8 years, as opposed to the 3 and 5 years for the previous phases.
- Auction was the default method for allocating allowances, rather than free allocation.
- Harmonized rules for the allocation of remaining free allowances.
- The establishment of a New Entrants Reserve with 300 million allowances to fund the diffusion of renewable energy technologies and carbon capture and storage through the NER 300 program.

During this phase, the EU ETS matured significantly. To avoid adverse consequences like those experienced during the 2008 financial crisis, the European Union introduced a protective mechanism known as the Market Stability Reserve (MSR) in 2015. The MSR acts as a reserve of emission allowances, aiming to support the effectiveness of the EU ETS, promote market stability, and enhance resilience to external economic shocks, like the one witnessed in 2008, which caused a 50% drop in EU ETS emission allowance prices within a few months. The Market Stability Reserve is triggered whenever there is a reduction in the demand for emission allowances. It stabilizes prices by adjusting the total allowances in the market. As reported by the World Bank's "State of Carbon Price 2021" report [41], the recent COVID-19 pandemic had similar effects to those seen in 2008, causing a sharp decline in permit prices, although not as severe as in Phase 2.

The mechanism works as follows: if there is an excess of Circulating Emission Allowances (CEAs) exceeding 833 million units, 12% of the surplus permits are removed and added to the reserve. If there is a shortage of allowances in the market, with less than 400 million units, allowances are transferred from the reserve to the market. The goal is to maintain stable allowance prices.

Starting from 2018, the European Commission has been publishing the number of CEAs. According to Article 1 of Decision (EU) 2015/1814, the total number of CEAs is determined by considering several factors, including demand, supply, and the number of allowances stored in the MSR.

Phase 4 (since 2021)

To achieve climate neutrality in the EU by 2050, the European Commission adopted in 2021 the intermediate goal of achieving a net reduction of at least 55% in greenhouse gas emissions by 2030 (known as the FIT 55 target). The legislative package involves the revision of various EU climate-related laws, including the EU ETS. Currently in effect until 2030, phase 4 of the EU ETS hence imposes a declining annual cap on emissions, decreasing by 2.2% each year [42].

The COVID-19 pandemic brought about significant restrictions, leading to a substantial reduction in the demand for emission allowances. This, in turn, had important consequences for the price of carbon allowances, as visible in **Fig. 3.8**. However, MSR played a crucial role in reducing the surplus of allowances in circulation and facilitating the increase in their price [43].

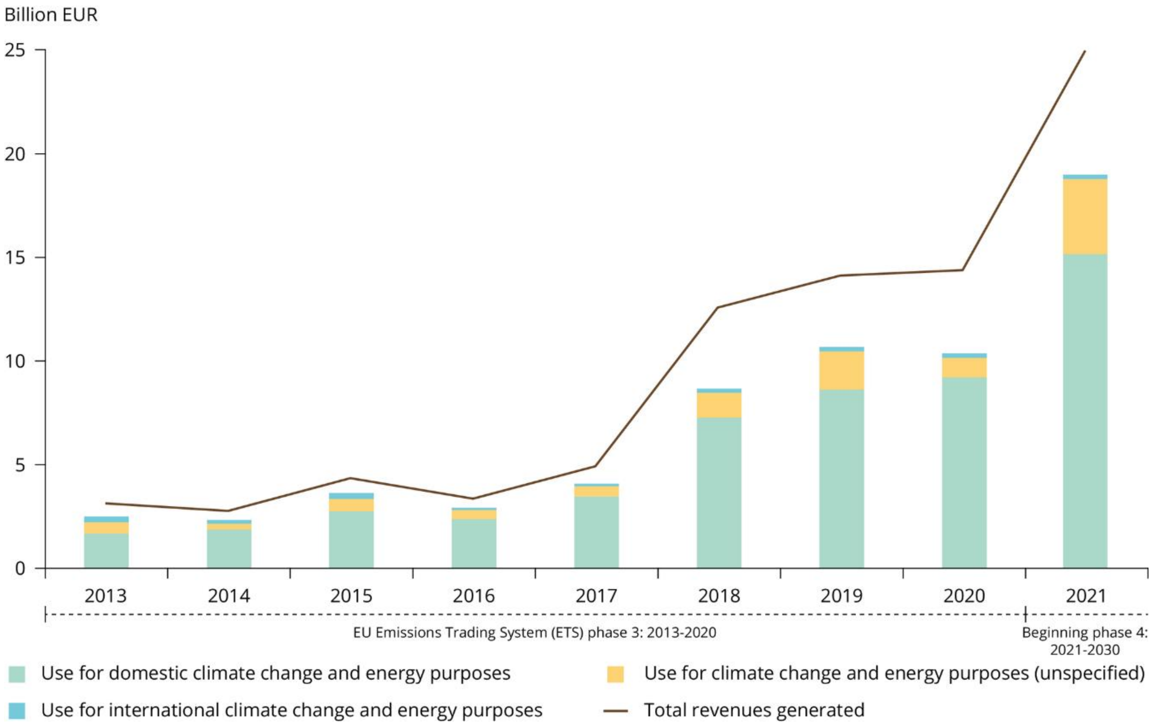


Fig. 3.10 – EU ETS auctioning revenues and reported usage, EU-27, 2013-2021 [45].

The European Union encourages its member states to allocate at least half of the revenues generated from the ETS to climate and energy-related purposes. Recent estimates indicate that the objective was generally met, with around 72% of ETS revenues directed towards climate and energy goals in 2020 [44], as also visible in **Fig. 3.10**. The FIT-55 target aims to increase this allocation, eventually earmarking all auction proceeds for climate and energy objectives.

Most of the auction revenues from the EU ETS are redistributed to all member states based on their verified emission shares. For the sake of solidarity, 10% of the proceeds are distributed exclusively among low-income member states [46]. Furthermore, 2% of the total allowances are auctioned to fund the Modernization Fund. This fund is geared towards modernizing energy systems, enhancing energy efficiency, and supporting a socially equitable transition to a low-carbon economy. The Innovation Fund's total funding depends on the carbon price, and it may amount to about €40 billion from 2020 to 2030, calculated by using a carbon price 75 €/ tCO_2eq. This funding is intended for the commercial demonstration of innovative low-carbon technologies, with the goal of bringing industrial solutions to the market to decarbonize Europe and support its transition to climate neutrality.

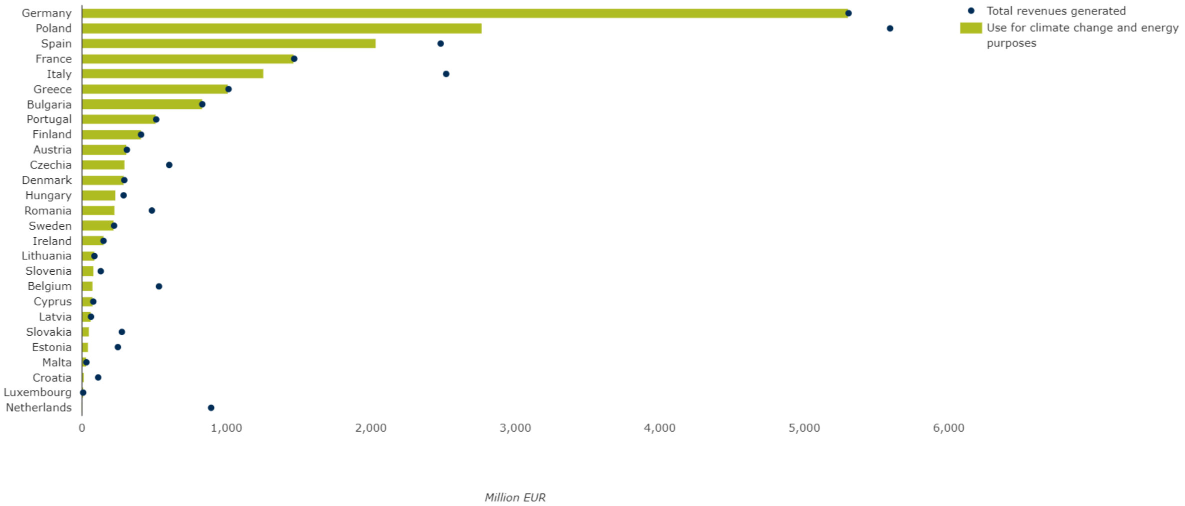


Fig. 3.11 – EU ETS Auctioning revenues and reported usage in 2021, for each Member [45].

Member states differ in terms of the amounts and shares of revenue allocated to climate and energy-related purposes (**Fig. 3.11**), as well as the specific measures they undertake. For instance, France allocates up to 420 million euros annually from auction proceeds to improve household energy efficiency and provide financial support for the social needs of low and middle-income families [47]. Other countries, such as Hungary and Estonia, focus on transportation, using ETS proceeds to fund electric charging stations and support the purchase of electric cars and buses. Germany also dedicates a portion of its revenues to international, European, and national climate programs. Another significant distinction lies in whether member states earmark their revenues or direct them to the general budget. Italy, for instance, allocates a portion of its revenues (77.5 million euros) to initiatives aimed at enhancing energy efficiency and insulation, as well as providing financial support to address social aspects in lower- and middle-income households. The EU appears to be nearly evenly split on this matter, with ten member states allocating auction proceeds, eleven not earmarking them, and six adopting a hybrid approach [47].

3.5.1 EU ETS impact on emissions

The EU ETS has been in place since 2005 and since its early stages has been the object of investigation concerning its role in emissions mitigation. Although the theory behind ETS is clear, it is not as easy to evaluate its effectiveness in empirical work.

Some studies failed to support the idea that ETSs reduces carbon emissions. On of the early studies from Jaraitė et al. [48] used a dataset of about 5’000 Lithuanian firms between 2003 and 2010, to assess the impact of the EU ETS on the environmental and economic performance of participating firms. Using a matching methodology, the impact of EU ETS participation on CO_2 emissions, CO_2 intensity, investment behavior and profitability of participating firms was assessed showing that ETS participation did not lead to a significant reduction in CO_2 emissions, a slight improvement in CO_2 intensity was identified. ETS participants also retired part of their less efficient capital stock, and made additional investments from 2010, although modest. Interestingly, the EU ETS did not represent a drag on the profitability of participating firms.
Calel et al. [49] also found that the EU ETS did not lead to significant emission reductions in UK firms but improved their economic performance.

However, literature on the topic is abundant with sectorial studies that confirm the effectiveness of the EU ETS. Colmer et al. [50] analyzed the French manufacturing industry, finding that regulated firms reduce emissions more than unregulated ones.
Bayer et al. [51] tried to assess whether the EU ETS reduced emissions despite low prices of the initial phases by estimating counterfactual emissions using a statistical model and an original sectoral emissions dataset. The authors reported that the EU ETS saved about 1.2 billion tons of CO_2 between 2008 and 2016 (3.8% of total EU-wide emissions) relative to a world without carbon markets, or almost half of what EU governments promised to reduce under their Kyoto Protocol commitments and that emission reductions in sectors by the EU ETS were higher. They motivated results by arguing that if a carbon market is a credible institution that can plausibly become more stringent in the future, firms might cut emissions even though market prices are low. In this case, low prices can be a signal that the demand for carbon permits weakens because of reduced emissions.

Fageda et al. [52] used a policy change in the EU ETS to measure the impact of carbon pricing on aviation. Originally, all flights arriving at or departing from airports within the European Economic Area (EEA) were covered by EU ETS, regardless of their origin, destination, or the nationality of the airline. However, this approach sparked significant controversy and, in response to substantial international pressure, the European Commission revised its stance, narrowing the scheme's scope to encompass only flights within the EEA, irrespective of the airline's nationality. Consequently, as of 2013, certain air routes (i.e., those within the EEA) became subject to regulation, while others remained unregulated, specifically flights with at least one endpoint outside the EEA. These categories were designated as treated and control groups, respectively, in an econometric analysis employing a difference-in-differences methodology. The research findings indicate that the EU ETS led to a 4.7% reduction in emissions on regulated routes compared to the counterfactual scenario, despite the relatively lenient measures imposed on airlines, with approximately half of the allowances being allocated for free. When focusing on short-haul flights (under 1’000 km), the emission reduction was even more pronounced at 10.7%. Notably, while low-cost airlines experienced a substantial reduction in emissions (11%), the effect was not statistically significant for network airlines. The diminished relative growth in emissions on treated routes compared to control routes can primarily be attributed to a slower increase in the number of flights. According to the authors, the EU ETS contributed to mitigating emission growth by an estimated 3 Mt CO_2 per year during the analyzed period, albeit falling short of achieving an absolute reduction in emissions within the sector, as necessary. Therefore, supplementary measures such as investments in enhancing national and international rail connectivity were proposed, particularly given the more significant emission reductions observed in short-haul flights competing with trains. Additionally, recommendations were made for eliminating the allocation of free allowances (not completely justified in the aviation sector given its international dimension) and expanding the geographical reach of the policy.

An issue related to ETSs which is unfortunately difficult to measure is that of rebound effects [53]. According to the classification proposed by Greening et al.[54] they divided the rebound effect into four main categories: direct rebound, indirect rebound, economy-wide rebound, and macroeconomic rebound. The direct rebound is due to energy consumption increases due to improved energy efficiency, causing a decrease in the unit price of energy, ultimately leading to an increase in energy usage per

capita [55]. Indirect rebound occurs when consumers spend their savings from energy efficiency improvements on other goods and services [56].
The economy-wide rebound refers to the fact that energy efficiency improvements result in the alteration of prices, demand quantities, and production in the selected unit [57] and includes direct and indirect effects. The macroeconomic rebound effect combines economy-wide and indirect rebounds. Energy efficiency improvements bring macroeconomic growth, which increases energy consumption This mixed effect is named the macroeconomic rebound [58]. Bolat et al. [59] looked for evidence of an EU ETS macroeconomic rebound effect using both a panel estimation approaches and Granger causality analysis. Their findings suggest the presence of a self-enforcing macroeconomic carbon rebound which may intensify globally since economic growth in the EU ETS will result in positive spillovers in other economies. The creation of a single global ETS that covers all sectors would eliminate the macroeconomic rebound effect. However, although a global carbon market could work in theory, this seems impossible to achieve with the current state of international cooperation. For these reasons, the need for a holistic perspective to avoid rebound effects when designing climate policies was highlighted.

Finally, concerning the impact that these emission reductions have had on economic performance of covered companies, Dechezleprêtre et al [60], concluded that EU ETS had no significant impact on profits and employment, and led to an increase in regulated firms' revenues and fixed assets. Although recent (2023) the study refences however concerns the period between 2005 and 2012. The impact of increasing allowances prices remains hence to be seen in light also of the new tools (e.g. the CBAM) which are to be implemented.

3.5.2 Accounting of carbon removals

The emissions overseen by the EU ETS are projected to reach net zero by 2045, followed by considerable net negative levels by 2050. Presently, there exists no mechanism for integrating CO_2 removal credits (CRCs) into the EU ETS framework. European legal requirements currently exclude biological-based CO_2 removal methods from the EU ETS if they fall within the scope of the Regulation on land, land use change, and forestry (LULUCF) [61]. If they do not fall under the LULUCF scope, installations that capture and transport CO_2 for subsequent storage are currently included in the EU ETS. Conversely, the current ETS Directive does not allow for the creation of additional allowances through CO_2 removal, as it requires the presence of "positive" emissions for EU ETS applicability.

There's uncertainty regarding whether the current ETS Directive contains clauses to include Negative emissions technologies, deviating from its general framework regarding the direct nexus between emitting activities and the use of emissions-reducing technologies. While BECCS (see *Section 5.2*) activities exhibit the necessary link between emissions, capture, and storage, they cannot be accounted for in the EU ETS, as installations exclusively using biomass are presently not covered by the ETS Directive. Consequently, the current ETS Directive lacks provisions for generating independent allowances under the EU ETS by removing CO_2 from the atmosphere and offering them for sale [61].

The integration of CRC supply into the EU ETS could enable more ambitious net emissions reduction targets. However, achieving the EU's goal of greenhouse gas neutrality by 2050 and net negative emissions thereafter will require suitable incentive systems for CO_2 removal [61]. It's important to open up the EU emissions trading system, the primary climate policy instrument, to NETs from a regulatory perspective, a matter the commission is expected to report on by 2026.

3.6 Carbon leakage and contrasting measures

The lack of a global carbon market and the difference in carbon prices between countries part of different ETSs and those without carbon pricing schemes, raise concerns about the potential of ETS to cause a phenomenon referred to as "Carbon leakage". Carbon leakage refers to the risk that companies in

countries with stricter climate policies will move their production to countries with less stringent policies, to reduce their costs. Nominal carbon prices as of April 1st 2023 are shown in **Fig. 3.12**.
Empirical research has, thus far, revealed little indications of the effective existence of carbon leakage. Nevertheless, it is worth noting that carbon prices have remained very low up to very recently, even though they have started to rise and there is a high likelihood that they will rise more in the future. Indeed, a recent study from the European Central Bank [62] reported that some carbon leakages has already occurred and that declining emissions in regulated industries within the EU have been partially counterbalanced by an intensification elsewhere. Furthermore, that study argued that the ETS imposed a burden on companies in regulated sectors since for comparable increases in production emission intensity, the gross output of companies within the EU decreased more significantly than that of companies located outside the EU.

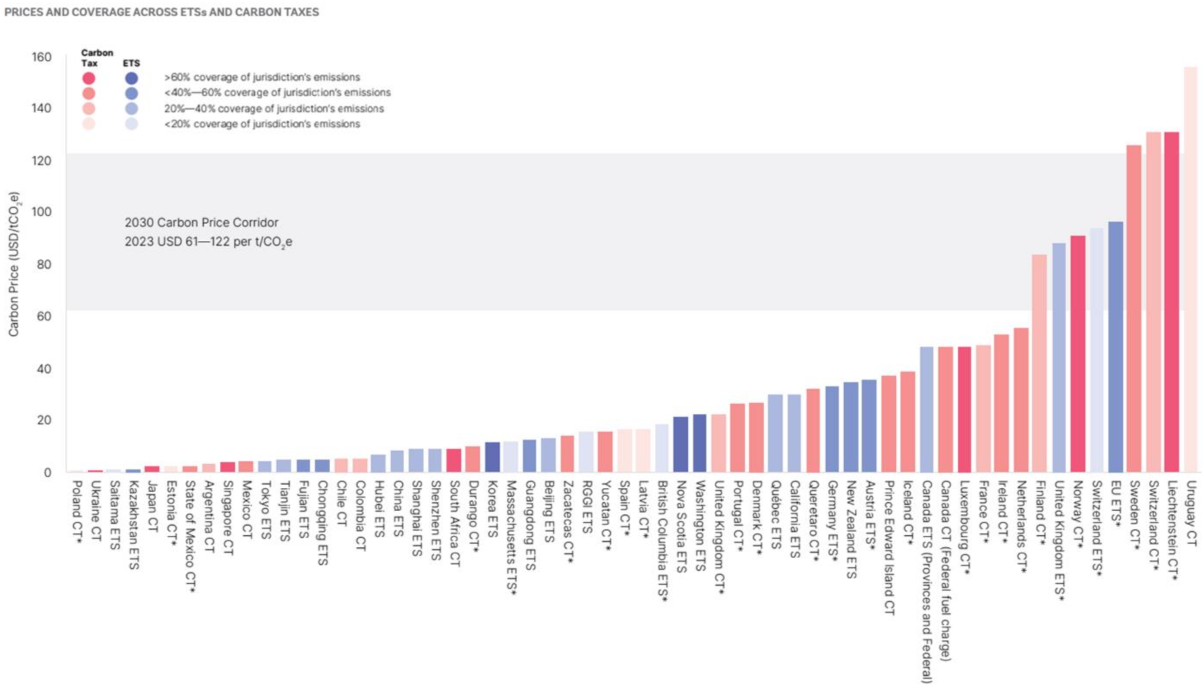


Fig. 3.12 – Nominal carbon prices on April 1st 2023 [22].

The price of emission permits inevitably translates into increased direct and indirect costs for producers subject to stricter regulations. This leads to a higher risk of losing market share to foreign competitors who face fewer constraints. In the long term, this situation may lead to the closure of production facilities in countries with stricter regulations and subsequent openings in countries with lower or absent emission restrictions. To safeguard the competitiveness of industries covered by the EU ETS, national governments often allocate a higher proportion of free emission allowances to sectors considered at significant risk of relocation. Additionally, an official list of sectors and sub-sectors deemed at significant risk of carbon emission relocation is compiled every 5 years by the European Commission with the agreement of member states and the European Parliament.

An initial list was compiled in 2010 (CE 10251 del 24/12/2009) and in validity until 2014. A second list was prepared in 2014 (CE 7809 dated 10/24/2014) intended for application in 2015-2019. However, in 2017, it was decided to extend its application until 2020.
For Phase 4 (2021-2030), in 2019, the Commission adopted a new decision (EU 2019/708 OF THE COMMISSION dated February 15, 2019) that integrates Directive 2003/87/EC. To prevent the relocation of CO_2 emissions, this decision defines the extension of free allowances even after 2020. Transitional free allocation should continue to be allocated to facilities in sectors and sub-sectors at risk of CO_2 relocation. The decision updates the list, identifying a total of 245 industrial sectors falling under the categories of "Extractive Activities" and "Manufacturing Activities."

The allocation of free carbon allowances affects the effectiveness of an ETS. If these allocations are overly generous, it can diminish the incentive for firms to reduce their emissions. This topic has sparked significant debate and a growing body of literature in recent years. It's essential to understand how an ETS can impact the relocation of emissions, as this has far-reaching environmental, economic, and social implications. The environmental goals of a domestic carbon pricing policy would be undermined if it led to increased emissions in other regions. In the worst-case scenario, carbon leakage could even result in a global increase in emissions, as some studies have argued [63].

In an effort to overcome these drawbacks, the “Fit for 55” package included a proposal for the creation of a European CBAM which would require EU importers to purchase allowances at a price corresponding to the carbon price prevailing in the EU as determined by the weekly average auction price for allowances under the ETS, thus effectively levelling the field between intra-EU production and imports. Imports from countries with a comparable carbon pricing mechanism will be eligible for a deduction equivalent to the price paid at the source, a crucial measure to uphold the core principle of national treatment outlined by the World Trade Organization (WTO). However, no partial waivers or compensations will be provided for imports that emit fewer GHGs than their EU counterparts. With the full implementation of the CBAM in 2026, companies in energy-intensive and trade-exposed sectors will no longer receive free allowances since protection of EU industries from foreign competition will become less necessary.

The CBAM is a unilateral trade measure proposed by the EU not agreed upon with the WTO. While this could create a risk of litigation and retaliatory actions that could undermine EU foreign trade and industry competitiveness legal experts generally agree that the extension of the ETS to imports complies with WTO law since it puts domestic and foreign products on an even footing. Challenges include the lack of international coordination, variations in national ETSs, and differences in methodologies for calculating emissions. Despite informal consultations and careful revisions, it remains possible that the implementation of the CBAM could lead to legal disputes and retaliations, ultimately harming EU foreign trade and industry competitiveness. To address these challenges, there's consideration for stronger coordination among countries, such as linking national ETSs, which could serve as a long-term solution to reduce the need for CBAM and promote convergence in emissions calculation methodologies at the national level.

3.6.1 Carbon leakage and ETS in an evolutionary model

Antoci et al. [64] proposed a theoretical framework to address the issue of carbon leakage and to get a deeper understanding on the ETS-related risks of carbon leakage. The authors presented a simple evolutionary model in which each firm must decide between two alternative strategies: keeping production at home or shifting it abroad. Firms decide their production location looking only at current profits, and specifically at which of the two strategies is more profitable at present but can revise their strategy based on their relative performance. This model can be used to examine the influence of some key elements of the ETS design (e.g., the emissions cap, the number of permits given for free and/or the floor price level) on the decisions of firms concerning their output production, location of the production and emissions abatement.

The evolutionary model

The model considers a scenario involving numerous firms producing a uniform good using polluting technology. These firms fall into two categories: home firms (*h-firms*), which operate within a domestic country with an emissions trading system, and relocating firms (*r-firms*), which relocate their operations to foreign countries. The parameter x represents the proportion of *r-firms* relocating, while $1-x$ is the fraction of *h-firms* remaining in the domestic country out of a total N firms.

Each h-firm and r-firm produces goods and thus pollutes. It is assumed that each unit of production results in one unit of emissions, and we denote this as q_i for both types of firms (i = h, r). Firms aim to maximize their profits and both the output market, and the domestic carbon market are assumed to be perfectly competitive. The ETS regulator in the domestic country can offer domestic firms a certain number of free permits, denoted as F, to deter them from relocating their production abroad. These permits may or may not be sufficient to cover the emissions of *h-firms* (i.e., $F \geq q_i$). If the number of permits is not sufficient to cover their emissions (i.e., $F \leq q_i$), firms have the option to purchase additional permits or reduce emissions through abatement efforts, represented by z. Both fixed and variable production costs are applicable to the firms. Variable costs and abetment costs are both assumed to follow a quadratic function of production. Hence, the profits of each firm that stays at home are:

$$\Pi^h = p \cdot q_h - \frac{C_h^v}{2} \cdot q_h^2 - C_h^f - \frac{\theta}{2} \cdot z^2 - a \cdot \max\,(0, q_h - z - F) \tag{3.1}$$

where p indicates the price of the produced good, q_h the amount produced by the firm that remains at home, C_h^v and C_h^f denote the variable and fixed costs of the firm, respectively, and a is the price of the emission allowances. Finally, $\theta > 0$ is a parameter which measures the (in)efficacy of the abatement technology: the higher θ, the higher the marginal cost of abating emissions using a given technology (the marginal abatement cost being equal to $\theta \cdot z$). The last term in brackets on the right-hand side of **Eq. (3.1)** represents the demand of emission allowances of the firm $\max\,(0, q_h - z - F)$. Allowance demand is lowered by the permits received for free and by the abatement activities which set the firm free from the need to purchase permits.

Every *h-firms* determines its ideal production and abatement levels to optimize profit, adhering to non-negativity restrictions on q_h and z. These decisions depend on exogenously established prices for output (p) and carbon allowances (a), with h-firms acting as price-takers in both markets. These factors lead to three distinct solution sets, each maximizing the profit function, depending on the level of the output price p [64]:

- if $p \leq C_h^v \cdot F$, then:
  $$q_h^* = \frac{p}{C_h^v}, \quad z^* = 0, \; d_a^* = 0 \tag{3.2}$$
- if $C_h^v \cdot F \leq p \leq \frac{(C_h^v \cdot F + a) \cdot \theta + a \cdot C_h^v}{\theta}$, then:
  $$q_h^* = \frac{\theta \cdot F + p}{C_h^v + \theta}, \quad z^* = \frac{p - C_h^v \cdot F}{C_h^v + \theta}, \; d_a^* = 0 \tag{3.3}$$
- if $p \geq \frac{(C_h^v \cdot F + a) \cdot \theta + a \cdot C_h^v}{\theta}$, then:
  $$q_h^* = \frac{p - a}{C_h^v}, \quad z^* = \frac{a}{\theta}, \; d_a^* = \frac{(p - a - C_h^v \cdot F) \cdot \theta - a \cdot C_h^v}{\theta \cdot C_h^v} \tag{3.4}$$

Given the intervals defined in **Eq. (3.2)**- **Eq. (3.4)**, q_h^* in **Eq. (3.3)** is clearly greater that in **Eq. (3.2)**, q_h^* in **Eq. (3.4)** surpasses that in **Eq. (3.3)**, and $z*$ in **Eq. (3.4)** is greater than in **Eq. (3.3)**. As shown in **Eq. (3.2)**- **Eq. (3.4)**, it is possible to distinguish three distinct scenarios, each with optimal values based on the price level of the produced good:

1) At a relatively low price p, each *h-firm* produces an amount of output (and emissions) less or equal to the number of free permits received $(q_h^* = p/C_h^v)$. Hence, no additional permits are needed ($d_a^* = 0$), and no abatement activity occurs ($z^* = 0$), as shown in **Eq. (3.2)**.

2) When the price p falls within intermediate values (see **Eq. (3.3)**), *h-firms* increase production but prioritize emission abatement (resulting in a positive z^*), rather than purchasing extra permits beyond those received for free ($d_a^* = 0$). Here, the permit price is relatively high, being equal to $a \geq \theta \cdot \frac{p - F \cdot C_h^v}{\theta + C_h^v} > 0$, which motivates firms to adopt cleaner technologies to avoid permit purchase costs.

3) Finally, at a relatively high output price p (**Eq. (3.4)**), firms intensify both production, since $\frac{p-a}{C_h^v} > \frac{\theta\cdot F+p}{C_h^v+\theta}$, but also their abatement levels. However, in this scenario, firms also purchase a positive number of permits ($d_a^* > 0$) due to the pollution price ($a < \theta \cdot \frac{p-F\cdot C_h^v}{\theta+C_h^v} > 0$) becoming relatively low.

On the other hand, relocating firms (*r-firms),* are characterized by different economics. In this case, the profit function is:

$$\Pi^r = p \cdot q_r - \frac{C_r^v}{2} \cdot q_r^2 - C_r^f \tag{3.5}$$

Relocating firms determine decide how much to produce to maximize their profit function (**Eq. (3.5)**), where q_r stands as their sole variable of choice. Unlike *h-firms*, *r-firms* neither engage in emission abatement nor purchase emission allowances. Consequently, in contrast to *h-firms*, their profit function excludes the last two terms on the right-hand side of **Eq. (3.1)**. Solving the maximization problem specific to *r-firms*, the optimal production quantity for *r-firms* becomes:

$$q_r^* = \frac{p}{C_r^v} \tag{3.6}$$

This equation signifies that the marginal cost of production for the foreign firm ($q_r \cdot C_r^v$) is equal to the output price p at equilibrium.

From solving the above optimization problems for both *h-firms* and *r-firms*, equilibrium conditions on the output and permits markets can be derived. For the output market, total supply S is expressed as:

$$S = x \cdot N \cdot q_r^* + (1 - x) \cdot N \cdot q_h^* \tag{3.7}$$

Assuming a standard linear demand function, the equilibrium price on the output market is:

$$p = \bar{p} - \alpha \cdot [x \cdot N \cdot q_r^* + (1 - x) \cdot N \cdot q_{rh}^*] \tag{3.8}$$

Where $\alpha > 0$ and $\bar{p} > 0$ are parameters.
Concerning the permits market, the aggregate demand D_a is equal to the individual demand of permits ($d_a^* = q_h^* - z^* - F$) multiplied by the overall number $(1 - x) \cdot N$ of *h-firms*:

$$D_a = (q_h^* - z^* - F) \cdot (1 - x) \cdot N \tag{3.9}$$

Indicating with $\bar{Q}$ the number of permits issued by the regulator (the emissions cap of the ETS), the share permits allocated for free to each *h-firms* to deter production relocation can be indicated with f. Hence, each *h-firms* receives $F = f \cdot \bar{Q}$ free permits, where $f > 0$. It's assumed the regulator cannot distribute all permits for free. Thus, even if all firms remain local (i.e., $(1 - x) \cdot N = N$, or $x = 0$), the number of free permits must be lower than the total issued by the regulator, hence $F \cdot N < \bar{Q}$ or alternatively, $f < 1/N$. The remaining permits, equivalent to the difference between the total permits $\bar{Q}$ and those allocated freely, are auctioned. The number of freely allocated permits is clearly given by the number of *h-firms* (i.e., $(1 - x) \cdot N$) multiplied by the number of free permits F received by each home firm. The equilibrium condition on the allowance market is therefore:

$$(q_h^* - z^* - F) \cdot (1 - x) \cdot N = \bar{Q} - F \cdot (1 - x) \cdot N \tag{3.10}$$

The expression on the left side shows the combined demand for permits from home firms, while the right-hand side is the overall permits sold by the regulator, net of those freely allocated. Simplifying, the equilibrium condition can be alternatively expressed as:

$$(q_h^* - z^*) \cdot (1 - x) \cdot N = \bar{Q} \tag{3.11}$$

It is assumed that the regulator establishes a minimum price level $\underline{a}$ (a floor price). Denoting the price that clears the permit market with a^*, if $a^* > \underline{a}$, then the aggregate demand for permits equals the total supply. In this scenario, the equilibrium condition in **Eq. (3.11)** applies. Conversely, if $a^* < \underline{a}$, an oversupply is observed in the permits market:

$$(q_h^* - z^*)|_{a=\underline{a}} \cdot (1 - x) \cdot N < \bar{Q} \tag{3.12}$$

In this case, the number of permits sold in the market at the floor price equals the actual demand: $(q_h^* - z^*)|_{a=\underline{a}} \cdot (1 - x) \cdot N$.

The last step of the model consists in simulating the evolutionary dynamics of the market. We assume that time is discrete (with $t = 0, 1, 2, \ldots, n$ denoting the single time periods). The percentage of firms that relocates is assumed to follow the so-called replicator dynamics [65]:

$$x_{t+1} = \frac{x_t}{x_t + (1 - x_t) \cdot e^{-\beta \cdot \Delta_t^{\Pi}}} \tag{3.13}$$

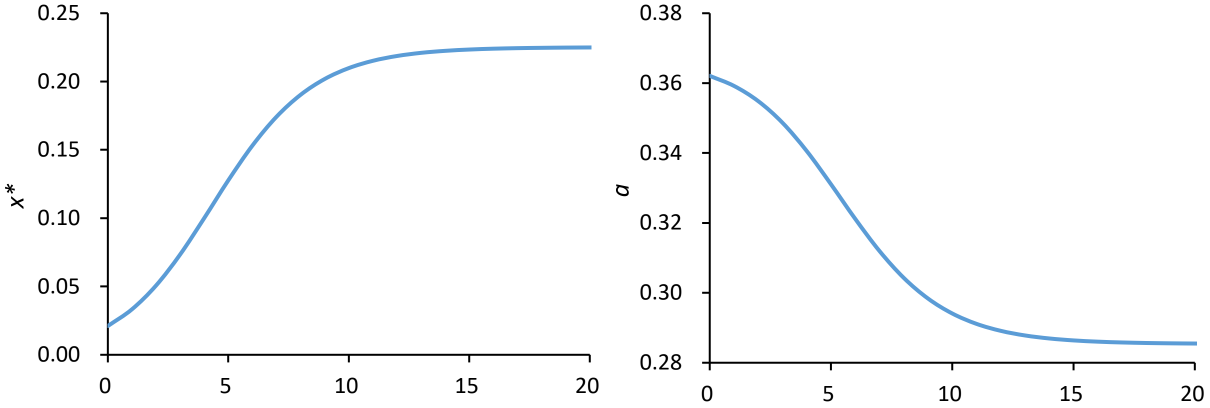
where $\Delta_t^{\Pi} = \Pi_t^r - \Pi_t^h$ indicates the difference in profit between *r-firms* and *h-firms* and $\beta > 0$ measures the speed at which firms change their choice (between relocating and staying). **Eq. (3.13)** implies that the future percentage of firms relocating (at time t+1) depends on the percentage of firms which relocate their activities in the present (at time t), indicating the existence of imitative behaviors in choosing between relocating and remaining. When $\Delta_t^{\Pi} = 0$, $x_{t+1} = x_t$, indicating a steady state where the percentage of relocating firms remains constant over time. Conversely, when $\Delta_t^{\Pi} > 0$, $x_{t+1} > x_t$, suggesting that if the advantages of relocating outweigh those of staying home, more firms will tend to relocate over time. The opposite is true if $\Delta_t^{\Pi} < 0$.

The above model proposed by Antoci et al. [64] was implemented in Python and used to examine the influence of some key elements of the ETS design. More details on the routine implementation are given in the Appendix (*Section 7.1)*.

Numerical simulations and results

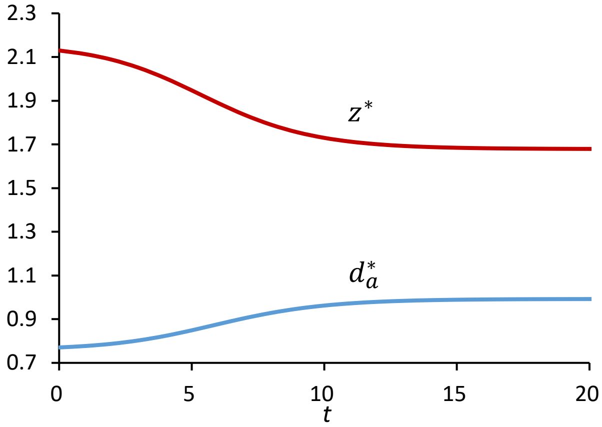
The model was used to simulate the influence of some of the key parameters of the ETS design, as shown in **Fig. 3.13** and **Fig. 3.14**.

For example, let's consider a scenario where most firms (98.7% of the total) initially function within the home ETS (x = 0.013, **Fig. 3.13(a)**). The parameters considered in the simulation are: N=50, $\bar{p}$=150, α=1, C_h^v=0.6, C_h^f=0.5, C_r^v=0.5, C_r^f=1.7, $\bar{Q}$=40, f=0.001, $\underline{a}$=0.1 and β=1.5. Given these values, the strategy of relocating becomes more profitable than staying home. Consequently, an increasing number of firms opt to move their production elsewhere, gradually elevating the share x until it reaches approximately 0.225, marking the stationary state. The migration of firms away from the home country to jurisdictions outside the ETS naturally reduces the allowance price, as shown in **Fig. 3.13(b)**. This diminishes firms' motivation to invest in abatement activities, leading to an increase in permit demand until both variables stabilize at their stationary state levels, around 1.7 and 1.0, respectively, as show in **Fig. 3.13(c)**.



(a) Share of firms that relocate abroad

(b) Permits price



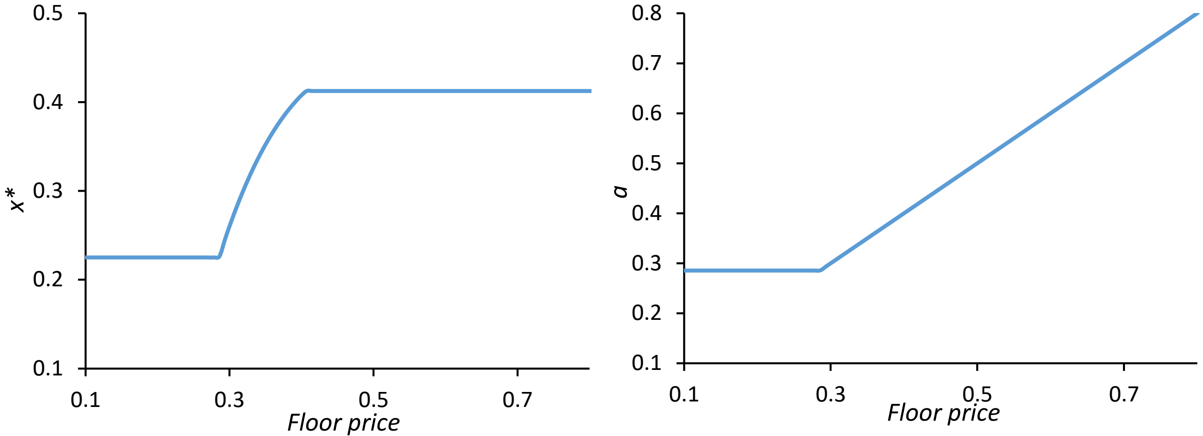
(c) Abatement activities and permits demand

Fig. 3.13 – Intemporal evolution of relocating firms (x^*), permits price (a), abatement activities (z^*) and permits demand (d_a^*).

The model can also be used to evaluate the effect of policy changes, like for example an increase in the floor price $\underline{a}$ (**Fig. 3.14**). As one might anticipate, this increases the number of firms relocating since it elevates the minimum cost of acquiring allowances. However, as depicted in the figure, the decision of firms to relocate remains unaltered at very low or high levels of the floor price. When the floor price remains below the market-clearing price (approximately $\underline{a} \simeq 0.3$ in **Fig. 3.14**), it has no effect on the variables under consideration. As the floor price surpasses the market-clearing price, the price of permits aligns with the floor price, leading to parallel growth in both variables (**Fig. 3.14(b)**). The increase in permits price triggers a gradual migration of firms toward non-ETS jurisdictions (x^* increases in **Fig. 3.14(a)**), a decline in permit demand (d_a^*), and an increase in abatement activities (z^*) to avoid the higher compliance costs (**Fig. 3.14(c)**).

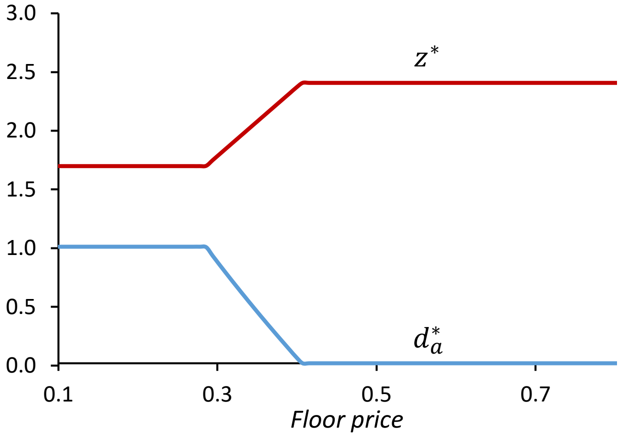
Once the floor price reaches a sufficiently high level (around $\underline{a} \simeq 0.4$ in **Fig. 3.14**), permit demand goes to zero. Consequently, firms' decisions regarding abatement and relocation become independent from the permit price (as firms stop purchasing permits). Consequently, both z^* and x^* stabilize once more, and further increments in the floor price cease to affect these variables.

The model can be used to simulate the effect of other variables like the total number of permits $\bar{Q}$, the share of free permits f, the efficiency of abatement technologies θ, etc. as shown in detail in [64].



(a) Share of firms that relocate abroad

(b) Permits price



(c) Abatement activities and permits demand

Fig. 3.14 – Evolution of relocating firms (x^*), permits price (a), abatement activities (z^*) and permits demand (d_a^*) at different values of the floor price ($\underline{a}$).

Evolutionary model summary and perspectives

In the absence of a unified global carbon market, individual carbon policies might inadvertently trigger carbon leakage effects, particularly if carbon prices rise to meet more ambitious emission reduction targets in the future. Carbon leakage poses a dual threat, impacting both the effectiveness and viability of domestic climate policies. If polluting activities relocate due to unilateral climate policies, it could negatively impact local production and employment without significantly reducing global emissions, potentially undermining the credibility of domestic climate initiatives.

Given the substantial variance in climate policy ambition among different regions, Antoci et al. [64] approached the problem proposing an evolutionary model representing the decision-making process of ETS-regulated firms regarding whether to maintain operations domestically or relocate production abroad to non-ETS countries. Firms in this model tend to imitate others and adopt strategies that yield the best average profitability among all firms. This approach enables the modeling of imitative behaviors commonly observed in economic systems, influencing firms' choices regarding the location of their production activities in a perfectly competitive market.
The analytical model simplifies the reliability of economic forces at play, thus should not be relied upon for quantitative results. Nevertheless, such model can represent as a foundational framework that can be expanded in various directions, to explore for example the existence of multiple Emissions Trading Systems (ETSs) with differing characteristics, thus allowing to evaluate spillover effects. In this context, the adoption of policy instruments such as the ETS in one country might trigger policy spillovers across nations. This dynamic could prompt other jurisdictions to adopt analogous policies if they aim to maintain trading partnerships. These interrelationships between countries hold significant implications,

as evidenced by the ongoing discussions surrounding the EU's proposition to introduce a Carbon Border Adjustment Mechanism. This type of model could also be used to model competitiveness between different sectors in each country. Moreover, another interesting extension of this type of model could be the introduction of a third strategy, i.e. investing in clean technologies.

All the above shows that this type of modeling could represent a valuable tool to analyze carbon leakage effects on ETSs and more research in this direction could enrich the debate on the subject.

3.7 The Voluntary market

Voluntary carbon offsets are a variant of the carbon credits used in compliance cap and trade programs. As presented in *Section 3.4*, carbon markets can be broadly categorized into:

- *Compliance markets*: Driven by binding emission reduction targets (e.g., Emission Trading Systems or other regulatory measures like taxes).
- *Voluntary markets*: Engaged by entities aiming to offset their emissions voluntarily.

Voluntary carbon markets operate independently of the mandatory schemes and participants in this market are not obligated to reduce their emissions. Such reductions or compensations are entirely voluntary, and companies can choose to participate due to a sense of social responsibility, shareholder pressure, or as a strategic move. While in compliance markets the regulator sets rules for measuring the emissions and validating carbon credits, voluntary carbon offsets are created, verified, and transacted outside of governments agencies. The compliance sector currently dominates the market, but voluntary carbon offsets can support a much greater range of activities in more countries [66].

Unlike a cap-and-trade system, the Voluntary Carbon Market (VCM) employs a project-based approach with no finite supply of allowances. Within the VCM, additional carbon credits can be generated through the implementation of environmental projects. Companies can purchase these credits to offset unavoidable emissions and achieve their emission reduction targets.
To be part of the VCM, each project must be deemed additional. This implies that the removal or reduction of carbon or greenhouse gases would not have occurred without the compensatory project. For instance, a project developer seeking to preserve a forest slated for logging must demonstrate that if the proposed project did not materialize, the forest would not exist.
In recent years, there has been a significant influx of capital and new players in the market. Alongside this, there has been increased scrutiny from the media, particularly regarding the quality of compensations. Advantages and Opportunities linked to the Voluntary Carbon Market are that it:

- Incentivizes investments aimed at preserving nature and the environment and promotes large-scale transition: indeed, even if all companies were to decarbonize their activities, the conservation the environment and biodiversity suffers from a severe lack of funding. Carbon credits provide a scalable and measurable way to direct funding toward climate projects worldwide that might otherwise struggle to take off.

- Fosters implementations of cost-effective action towards achieving global net-zero emissions: There remains a significant gap between government climate commitments and the reductions needed. The voluntary carbon market represents a practical and short-term option for companies to contribute to bridging this gap.

- Brigs new technologies, know-how, and funding to achieve and enhance a host country's contribution to the Paris Agreement. Many emissions calculation, monitoring, and verification methodologies that have been tested in voluntary markets are now being adopted in emerging compliance markets.

A carbon offset credit (or carbon credits) is a certified transferable instrument issued by governments or independent certification bodies to represent a reduction of one ton of CO_2eq of emissions.

In general, carbon credits can be obtained through purchases from project developers, brokers, or resellers. Alternatively, direct investment in a project and/or negotiating purchase options with developers is possible. Different acquisition methods have pros and cons, allowing companies to choose strategies based on transaction volumes and timelines.

Market participants

Designing, implementing, and operating projects requires the involvement of several stakeholders. Although these vary from project to project the main ones and their interactions are shown in **Fig. 3.15**
Project Owners are individuals, companies, or organizations that operate and own the physical installation where emission reduction projects are implemented.
Project Developers are entities or individuals with the intention to develop emission reduction projects, carrying-out activities such as project scoping, documentation filing, registration, certification, funding acquisition, project creation, and eventual sale to project owners.
Project Funders, such as banks, private equity firms, investors, and non-profit organizations provide funding or investment equity for projects, subject to rules set by offset program standards.

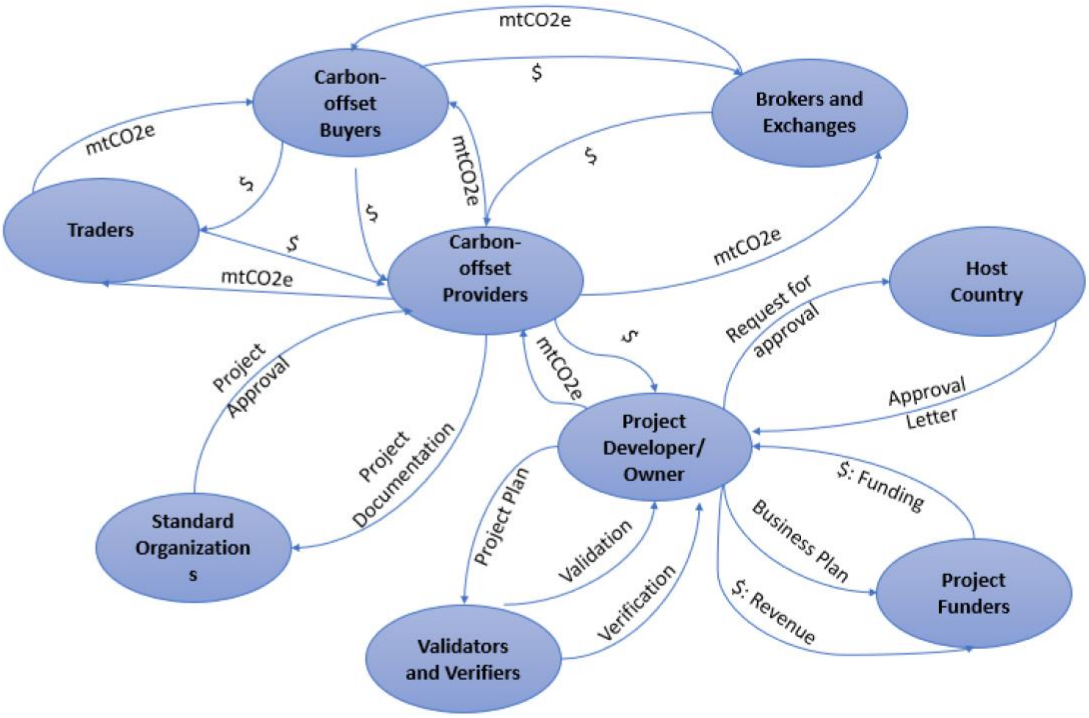


Fig. 3.15 – Voluntary Carbon Offset Market ecosystem map.

Validators and Verifiers (Third-Party Auditors) are required by most offset programs to validate and verify project baselines, projected, and achieved emission reductions. Accreditation processes are typically in place for these auditors.
Standards Organizations define rules and criteria for voluntary emission reduction credits, certify projects, and maintain registries recording credit transactions, issuances, and retirements.
Brokers and Exchanges, as in the case of many other commodities, these intermediaries can simplify credit identification, facilitating larger transactions and offering information on project quality. Some brokers also develop projects themselves. Additionally, several environmental commodity exchanges list carbon offset credits for sale, providing a relatively easy and fast but potentially less informative

option. Examples include Carbon Trade Exchange (CTX), European Climate Exchange (ECX), Climate Impact X (CIX), and AirCarbon Exchange (ACX).

Traders are professionals engaging in buying and selling emission reductions, leveraging market-price distortions and arbitrage opportunities.

Offset Retailers provide easy access to offset credits for consumers and businesses, sourcing from brokers or developers. For smaller buyers, approaching a reseller is a feasible option, offering access to credits from various projects. The best choice depends on time, resources, and required volumes. Larger volumes generally lead to discounted prices, creating economies of scale.

Final Buyers or End-Users are the individuals and organizations purchasing carbon offsets to offset their greenhouse gas emissions. Once retired, the offset can no longer be traded or retired again, and this retirement is recorded in the registry of the approving standards organization.

Buyers can identify interesting projects and support the development of new methodologies or technologies, investing in these projects and generating offset credits. However, this approach can be risky and time-consuming.

Alternatively, buyers can invest in a compensation project in exchange for rights to the generated carbon credits, providing a more comprehensive understanding of project strengths and weaknesses. Another option consists in negotiating directly with offset project to buy the project carbon offset credits upon issuance, usually through "Emission Reduction Purchase Agreements" (ERPAs). In some cases, offset project developers can have unsold credits available for purchase, thus avoiding some of the transaction costs.

Carbon credit quality

Five criteria, according to the Offset guide [67], determine carbon credit quality:

- Additionality: Credits must represent emissions reductions that wouldn't have occurred without credit sales.
- No Overestimation: Avoid overestimating baseline emissions; consider indirect project effects and prevent forward crediting issues.
- Permanence: Emission reductions credits cannot be reversed after credit generation.
- Exclusive Claim: Carbon offset credits must convey an exclusive claim to GHG reductions.
- No Significant Social or Environmental Harm: Credit generation must comply with laws, regulations, and international standards for social and environmental safeguards.

Compensation projects

Examples of the types of projects that can be invested in within the VCM include:

- Renewable energy technologies installation (wind, solar, bioenergy, etc.)
- Industrial gas capture and reutilization
- Energy efficiency projects
- Forest related initiatives (avoiding deforestation)
- Regenerative agriculture
- Clean water

Projects can be further categorized into three groups: Nature-Based Solutions (NBS) (encompassing forest restoration and avoided deforestation), Negative emission technologies (including carbon capture and storage, and Bioenergy with CCS), and Renewable Energy technologies installation in less developed countries. **Table 3.1** shows a comparison between voluntary and regulated markets.

Table 3.1 – Voluntary versus compliance markets overview.

	Voluntary Market	**Compliance Market**
Unit type	Verified carbon offsets generated via individual projects and freely tradable.	Emission allowances created by a central authority, allocated/auctioned to participants.
Price	Tends to be much cheaper.	Compliance credits tend to be more expensive because they are driven by regulatory obligations.
Supply/demand driver	Project developers create offset credits, while private sector voluntary carbon reduction drives demand	Supply centrally determined is demanded covered sectors.

According to Hamrick at al. [68], forest carbon credit transactions constituted more than half of the total off-set credit transaction volume in the voluntary market in 2014. The popularity of such transactions was achieved through flexible emission-reduction activities via Afforestation and Reforestation (AR), Improved Forest Management (IFM) and Reduced Emissions from Deforestation and Forest Degradation (REDD) projects, based on various carbon standards.

Indeed, the development of carbon projects in the voluntary market is governed by a number of major carbon standards. These frameworks employ various approaches to measure and verify reductions in carbon emissions. These frameworks offer validation procedures aimed at ensuring the credibility and reliability of projects aimed at emission reduction. Among the widely recognized standards are [69]:

- Verified Carbon Standard (VCS)
- Plan Vivo
- Gold Standard (GS)
- Climate Action Reserve (CAR)
- American Carbon Registry (ACR)
- ISO 14064
- The Climate, Community and Biodiversity Standard (CCB)

The verified carbon standard (VCS) was established in 2007 to standardize carbon units for quality assurance and increased fungibility of transacted carbon offsets [70]. Apart from its own carbon methodologies, the VCS accommodates projects employing methodologies established under the Clean Development Mechanism Climate Action Reserve. Certification from VCS is granted post-validation and verification through ex-post accounting. Notably, VCS does not encompass community co-benefit programs, but it allows for additional certification through Climate, Community and Biodiversity Standards (CCB) or Social Carbon Standard.

The Plan Vivo standard was established to promote projects with a variety of co-benefits extending beyond carbon emission reductions. These include social advantages for rural and underprivileged communities in developing nations, such as the promotion of sustainable livelihoods, ecological services, and biodiversity conservation. This standard establishes a community-oriented framework for the development of carbon projects, deviating from the rigor of measuring, reporting, and verification (MRV) processes to ensure the active involvement of local populations. Plan Vivo adopts an ex-ante accounting method, allowing projects to receive certificates prior to validation and verification [71].

The Gold standard (GS) was created to address the limitations of the Clean Development Mechanism as outlined in the Kyoto Protocol which solely focuses on carbon emission reductions. GS not only applies CDM-level methodologies to ensure the generation and transaction of high-quality and high-value carbon credits but also emphasizes the production of social and environmental co-benefits and the promotion of sustainable development. Certification of carbon credits occurs following the validation and verification of projects through ex-post accounting [71]. GS's Land Use and Forest (LUF) programs, developed through integration with the CarbonFix standard, aim not only for carbon emission reduction but also for the generation of ecological and social co-benefits.

The Climate Action Reserve (CAR) developed criteria and methodologies for carbon projects executed in North America. Additionally, it approves projects using methodologies sanctioned by the California Carbon Allowance trading program, allocating Carbon credits through ex-post accounting. CAR does not consider co-benefits initiated by projects for local communities, but it uses measures to prevent negative impacts from the projects.

The American Carbon Registry (ACR) manages its carbon registry to attain emissions reduction with high-quality requirements and facilitate the practical registration and management of carbon credits. ACR exclusively approves projects adhering to its own carbon standards and methodologies, issuing carbon credits through ex-post accounting. ACR takes into account co-benefits initiated by projects for local communities and actively works towards preventing negative impacts associated with projects.

ISO 14064 serves as an offset protocol, establishing international standards for GHG emissions reduction and management. Being regime-neutral, it is adaptable to all projects aiming to decrease GHG emissions. Diverging from other carbon offset standards, ISO 14064 does not provide tools or accounting methods, presenting its requirements in broad terms. For instance, it assumes project additionality for carbon accounting but does not furnish provide tests or tools for assessing it. The standard does not emphasize co-benefits and suggests conducting an environmental impact assessment if mandated by the region or host country.

The Climate, Community and Biodiversity Standards (CCB), established in 2005 by the Climate, Community, and Biodiversity Alliance, a collaboration of international NGOs, were created to evaluate and authorize the performance of land-based carbon projects in the realms of climate change mitigation and adaptation. Additionally, they assess the projects' influence on fostering co-benefits for local communities and biodiversity. While the CCB Standards lack their own standards for carbon reduction and measurement, they function as supplementary validation and verification for carbon projects developed under other carbon standards within the voluntary carbon market, such as VCS. Their certification focuses on acknowledging the projects' impact on both the local community and biodiversity [71].

Lee at al. [71] studied the characteristics of forest carbon credit transactions in the voluntary market using frequency and logistic regression analysis to evaluate if co-benefits of forest carbon projects are an important factor influencing carbon credit transactions. Forest projects were chosen because of their popularity but also because of the conspicuous co-benefits they can provide while achieving emission reduction. These include socio-economic benefits and environmental co-benefits which make them particularly attractive to buyers and are probably at the root of their popularity. In the study, retirement ratios of forest carbon projects were compared with respect to carbon standard, project type and co-benefit program. From the results of the study, the authors inferred that credits with potential co-benefits are preferred to those focusing only on emissions reduction. These findings suggest that developing co-benefits is important for strengthening the market competitiveness of forest carbon credits in the voluntary market and that more stringent carbon standards do not always guarantee credit transaction performance unlike for compliance markets.

3.7.1 Voluntary carbon offsets critics and concerns

The Voluntary Carbon Market has shown a significant growth over the past five years, with a 252% increase since 2017 [69]. It's estimated that the VCM attracted approximately $1.3 billion in investments during 2022, helping to offset around 161 million metric tons of greenhouse gas emissions [69]. However, following the Ukraine invasion, the growth of VCM experienced a slowdown in 2022 compared to the momentum gained in 2021. Nevertheless, according to the Taskforce on Scaling Voluntary Markets, the market is anticipated to grow approximately 15-fold, transitioning from 0.1 to 1.5-2 $GtCO_2eq$ of carbon credits annually by 2030 [72]. Some studies suggest that offset market possesses significant growth potential with estimates that the market may reach up to $50 billion in 2030

[66]. Furthermore, it's even forecasted that by 2050, this mechanism could yield a reduction of about 7-13 $GtCO_2eq$ of carbon credits per year [72].

However, with respect to compliance markets, voluntary carbon markets have so far been characterized by lack of information and of critical analyses [66]. For this reason, the need for quality assurance in order to maintain the credibility of voluntary offsets in the absence of government oversight has been recognized. The taskforce for scaling Carbon Markets [73]identified a number of issues with voluntary carbon markets which must be addressed for carbon markets to scale, including:

- Lack of market integrity
- Better governance
- Fragmentation of the carbon offset supply chain
- Weak validation and verification processes
- Fraud and money laundering
- Double-counting and spending
- Lack of pricing transparency
- Verification standards fragmentation
- Oversupply of poor-quality credits
- Regulatory uncertainty
- Limited supply chain pre-financing
- Lack of centralized registries between voluntary and compliance markets
- No visibility into revenue usage
- No default protection for OTC transactions
- Lack of transparency in OTC markets
- Unclear property rights
- Limited visibility into the project lifecycle
- Exclusion of certain project types from compliance schemes
- Lack of pricing for co-benefits of carbon credits
- Fragmentation of liquidity

For instance, the highly decentralized nature of the carbon credit supply introduces the risk of errors and fraud. This includes potential conflicts of interest between auditors and project developers, issues related to baseline modeling, and the risk of double counting when multiple standards are applied. The lack of price transparency and regulatory oversight further opens the door to potential money laundering.
Interviews conducted by Chen et al. [66] highlighted that participant reported key challenges within the voluntary carbon market to be the absence of market transparency, limited visibility on prices, and concerns regarding the quality of carbon offsets.

Another issue concerns the time needed for projects to generate offsets: it often takes several years for a project to generate a single offset, because of the lengthy time process of issuing and verifying offsets (for instance, offsets issued in 2020 were issued with a weighted vintage year of 2017, with some even dating back to 2003 [66]). As of 2020 [66], less than half of credits issued each year were retired by organizations. Issuances surpassed retirements, partly due to the historical trend of supply outpacing demand and also owing to the time gap between supply and demand.

Assessment of additionality is another challenge to offset quality. Though this could seem simple in theory, determining business as usual and baseline level of emissions is extremely difficult and complicated by issues arising because of asymmetric information. Offset providers know a lot about the projects in which they invest, but offset buyers know only what the providers tell them. Asymmetry gives rise to a standard source of market failure. Assessing additionality is hence difficult and it involves determining what level of emissions would have been without the incentives provided by the offset program. Because of these difficulties, third party organizations have emerged to set standards like the ones previously mentioned. Nevertheless, studies suggest that existing programs have awarded offsets that are not additional [66]. Verification is also complicated by the fact that sellers of carbon offsets may have little incentive to report information accurately to programs administrators. Finally, another issue concerns double counting which still exists in current systems.

There are also concerns about the permanence of emission reductions or sequestration, particularly in the case of forestry-based offsets which are subject to uncertainty concerning future land use, risk of fires and forest health. At the same time, as mentioned above, forest-based projects are frequently promoted because of the associated co-benefits ranging from wildlife habitat preservation to ecosystem services in a broad sense [74]. But because of their intrinsic uncertain nature some authors have suggested forest-based offsets [75].

Despite concerns, Chen et al. [66] did not conclude that these challenges signify that voluntary carbon markets cannot exist but based on prior studies into the economics of collaboration, they concluded that a reputation system, presently lacking, could induce to the success of this market. A robust reputation system, which could connect the diverse range of buyers and developers could be able to lower the cost of validating offsets in the market, thereby addressing simultaneously the issues of quality and cost.

Wang et al. [76] used a theoretical approach to study the unintended consequences of the participation in voluntary markets of the agriculture sector, which is the source of nearly a quarter of net emissions worldwide but has generally not been capped by compliance schemes. However, the sector has been mentioned as a source of voluntary net emissions offsets and a number of compliance markets include provisions (like the clean development mechanism) where capped entities can buy offsets from uncapped sectors. In the context of the agricultural sector, these offsets could be developed by adopting practices and actions that reduce GHG emissions, increase carbon sequestration or provide feedstock for bioenergy that replace fossil-based energy. Some examples include lessening emissions thorough enteric fermentation, manure management, rice cultivation, soil management, avoided deforestation, etc. The authors identified a trade-off in the baseline selection between additionality and participation. A generous baseline could lead to generating non-additional offsets (which would result could also result in an implicit relaxation of emissions caps in compliance markets), while too stringent baselines would eliminate the incentive for participation and might even encourage existing participants to reverse practices (*rebound effect*), stimulating emissions to then rejoin the program. Carbon leakage is also of concern since most programs are regional. Nevertheless, according to Wang et al. [76] these issues can be overcome by developing appropriate policies and participation limitations. For example, if producers are paid based on the emissions difference between current and improved practices per unit of land, they might be incentivized to expand the participating land, inducing a rebound effect. However, imposing a maximum participating land, equal to the preexisting area could solve the problem. Similarly, for sequestration/bioenergy, the authors suggested only paying relative to a standard for preexisting area and then dropping the standard to zero paying for additional participation. Although the analysis focused on the agriculture sector, this type of policy design could be applicable to other voluntary market settings and help increase the effectiveness of these schemes.

Offsets Use across direct taxation systems

Carbon offsets could also have a role in further increasing the flexibility of carbon pricing mechanism such as carbon taxes and ETFs, as they offer sectoral and geographical flexibility for jurisdictions to reduce greenhouse gas (GHG) emissions outside of the scope of their caron pricing schemes (**Fig. 3.16**).

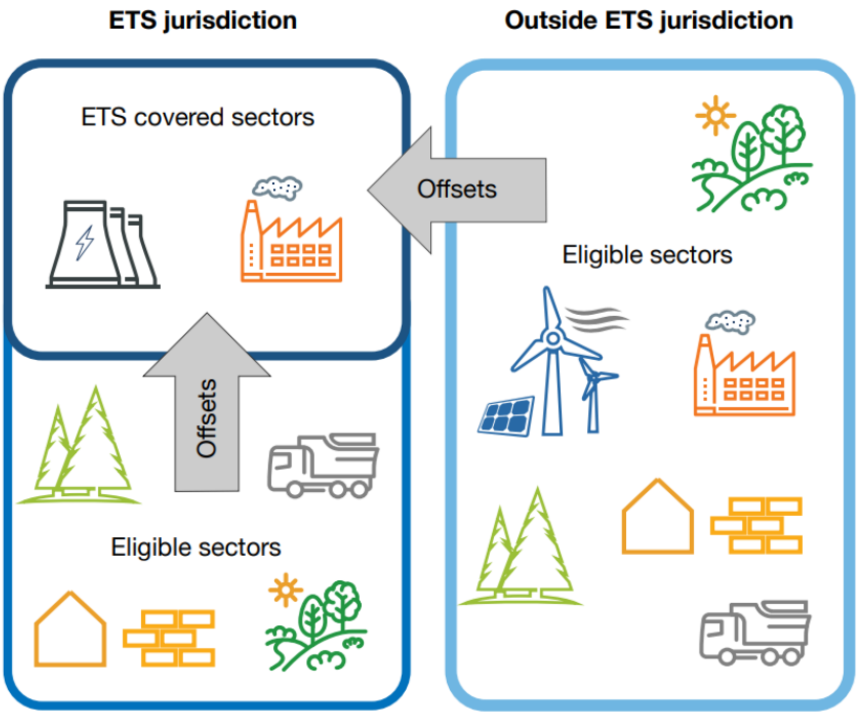


Fig. 3.16 – Offsets use in Emission Trading systems [77].

The International Carbon Action Partnership recently published an overview of Offsets Use across Emission Trading systems [77]. Depending on the regulations within an Emissions Trading Scheme (ETS), offsets may originate from projects either within or outside the geographical scope of the ETS jurisdiction, often referred to as 'domestic' or 'international' offsets respectively. Domestic offsets have been used in various ETS jurisdictions, including California and China. On the other hand, international offsets have traditionally played a bigger role in regions such as Europe, New Zealand, and South Korea. Offsets used in ETSs thus far have been primarily produced under the flexibility mechanisms of the Kyoto Protocol, particularly Certified Emissions Reductions (CERs) from the Clean Development Mechanism (CDM), and Emissions Reduction Units (ERUs) from the Joint Implementation Mechanism (JI) (see *Section 3.3*). Additionally, while historically ETSs have not heavily relied on offsets from independent mechanisms (Verified Carbon Standard, American Carbon Registry, Climate Action Reserve, etc.), a few existing and forthcoming ETSs are contemplating incorporating them.

Many ETSs worldwide (such as the European Union ETS (EU ETS), the New Zealand ETS (NZ ETS), the cap-and-trade programs of California and Québec, the Chinese pilots and the Chinese national ETS, South Korea's K-ETS, and Mexico's pilot ETS) have at some point included offset provisions in their system design. However, over time, there has been a trend toward an increased utilization of domestically sourced offsets over internationally sourced ones, as well as a shift toward the establishment of self-administered crediting mechanisms rather than relying on independently administered ones. Some systems, either initially or subsequently, have opted not to include offset provisions altogether. These systems include Germany, Austria, the UK ETS, Switzerland, the EU ETS, Nova Scotia, and Massachusetts.

An overview of offset use in current ETSs is shown in **Fig. 3.17**. California and Québec mutually allow offsets sourced from linked jurisdiction. The Swiss and EU ETS have not accepted offsets since 2021, while New Zealand has no longer accepted international offsets since 2015 (under the current legislation, the government can decide to readmit international offsets, contingent on access to high integrity sources). Korea allows domestic offsets as well as international CDM credits developed by Korean companies.

Fig. 3.17 – Overview of current offset use in ETSs [77].

Rules need to be established to determine the eligibility of offsets within ETSs. The criteria for offset usage have often been a subject of political debate and public scrutiny in ETS jurisdictions. There have been concerns regarding the potential risks offsets pose to the integrity of ETSs, particularly whether they offer polluting sectors an easier route to meeting their obligations compared to pursuing decarbonization efforts. Companies like Gucci and Netflix for example claim to be carbon neutral, largely thanks to offsets coming from forest protection certificates **Fig. 3.18**. To address these concerns, restrictions have been imposed on the types and quantities of offsets permissible for ETS compliance.

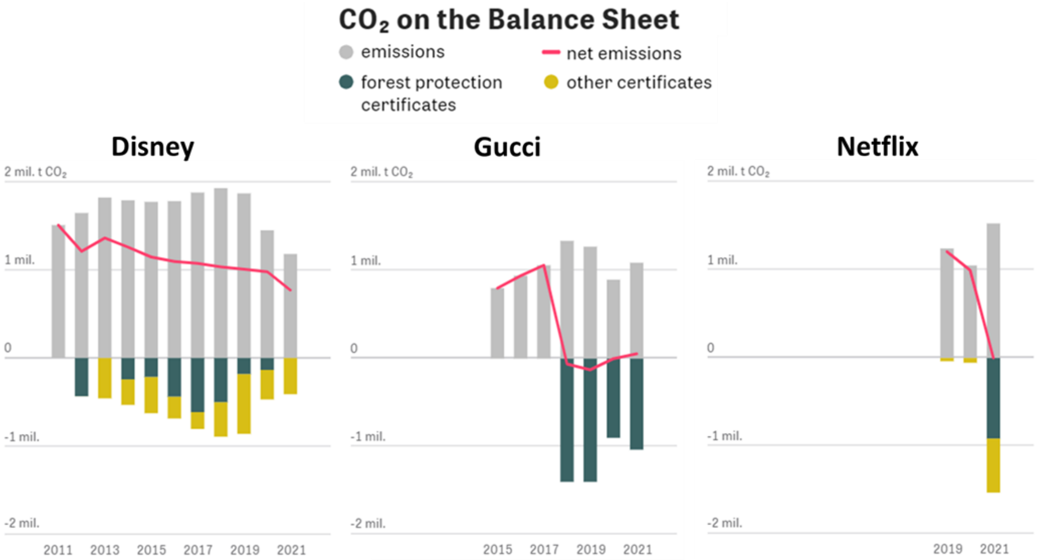


Fig. 3.18 – CO_2 on the Balance sheet of sample companies according to Verra registry.

In support of these claims, an international team of scientists and economists led by the University of Cambridge and VU Amsterdam studied emissions reduction achieved from deforestation and forest degradation (REDD). Indeed, West et al. [78] compared the actual effects of 26 projects in six countries with measurable baseline values and found that most projects had not significantly reduced deforestation. For projects that did, reductions were substantially lower than claimed. Specifically, out of a potential 89 million credits, only 5.4 million (6%) were linked to additional carbon reductions.

Another study by West et al. [79] also support the skepticism about the contribution of voluntary REDD projects to climate change mitigation. Comparing the crediting baselines established ex-ante by voluntary REDD+ projects in the Brazilian Amazon to counterfactuals ex-post based on a quasi-experimental synthetic control method, the authors found that the crediting baselines assume consistently higher deforestation than counterfactual forest loss in synthetic control sites. Although the gap is partially due to decreased deforestation in the Brazilian Amazon during the early implementation phase of the REDD+ projects considered, the study suggests that stricter measures should be taken to ensure the environmental integrity of carbon emission offsets. West et al. also estimated that CO_2 certificates generated (based on the forest lost prognosis **Fig. 3.19**) overestimated of around 400% the actual CO_2 saved, and an investigation carried out on these projects by Die Zeit and The Guardian identified several loopholes in the VERRA certification system.

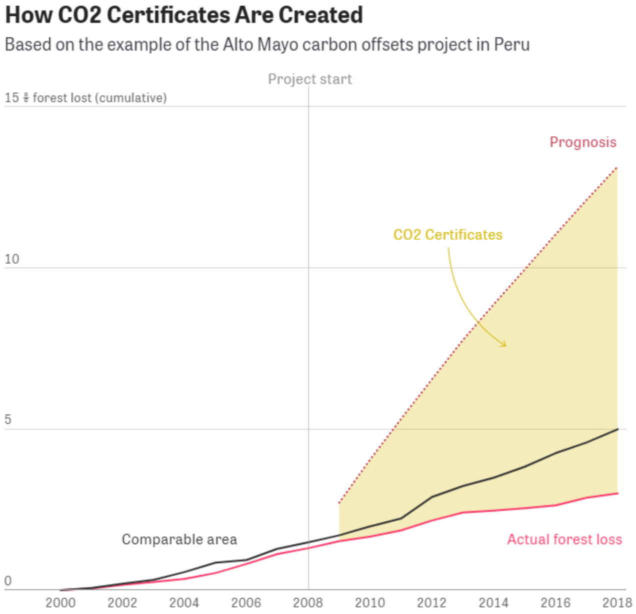


Fig. 3.19 – Actual CO_2 savings versus generated offsets based on the Alto Mayo offset project in Peru. Source: Global Forest Watch, Conservation International, West et al.

Therefore, when designing rules for offset utilization within an ETS two key considerations arise: quality criteria and quantitative limits. Through quality criteria, systems can limit eligible offsets to those activities considered to have higher environmental integrity. Through quantitative limits, a minimum share of abatement occurring inside the ETS can be ensured and potential price shocks caused by an influx of offsets can be limited.

Taking the example of the EU ETS, during its initial phase (2005-2007), regulated entities had unrestricted access to Clean Development Mechanism (CDM) and Joint Implementation (JI) credits; however, these offsets were scarcely utilized due to a crash of EUAs (EU allowances) prices towards the end of phase one. In phases two and three (2008-2020), the EU ETS was the primary demand driver for CDM and JI credits, being the largest carbon market globally at the time and one of the few that accepted international offsets. In the second phase (2008-2012), following a tightening of the EU ETS cap, offsets became increasingly appealing, albeit concerns arose regarding the additionality and environmental credibility of certain project types. Consequently, the EU implemented measures to regulate offsets, including the introduction of qualitative criteria and the ban on credits from industrial gas projects. Moreover, quantitative limits were imposed, with covered entities permitted to utilize CDM and JI credits up to a specified percentage as outlined in the National Allocation Plans of each EU Member State [77]. However, the 2008-2009 financial crisis reduced economic output in Europe, thereby creating an EUA oversupply and a corresponding price crash further exacerbated by these, the offset provisions which worsened the oversupply.

In the fourth phase of the European Union Emissions Trading Scheme (EU ETS), the utilization of offsets is prohibited. Nonetheless, in sectors presently outside the scope of the EU ETS, such as

transportation, buildings, agriculture, and waste management, certain flexibility is permitted. In order to incentivize further initiatives in the land use sector, as outlined in the Effort Sharing Regulation (ESR) by the European Commission in 2018, member states have the possibility to use collectively up to 262 million offsets throughout the 2021-2030 period to fulfil their respective national targets [77].
Furthermore, there have been growing discussions among experts and policy implementers regarding the potential integration of CO_2 removal technologies into the EU ETS. Carbon removal plays a pivotal role in realizing the European Union's goal of achieving net zero emissions by 2050. However, at present, there is no existing mechanism within the EU climate policy framework that permits the incorporation of such removal units.

So together with creating a cost reduction for covered entities, that of taking into account removals could be another compelling reason to combine direct carbon pricing schemes with offsets. The potential impacts on a carbon tax, including the country examples of Colombia, Mexico and South Africa, were investigated by Wang-Helmreich et al. [80] in order to bridge the existing knowledge gap on the topic.
The authors found that the introduction of offsets in carbon taxes opens opportunities including cost reductions for covered entities, emission reduction in sources generating offsets and positive spillover effects. These positive impacts can be further enhanced by devising appropriate policies aimed for example at discounting or reducing emissions from sources generating offsets, limiting crediting periods beyond which emissions reduction continue and using stringent baselines for business-as-usual levels.
Additionally, offsets could be used as bargaining chips in political negotiation, as was the case in Mexico and South Africa, where opposition against the introduction of a carbon tax was reduced significantly once the option to use offsets was allowed.
However, allowing offsets also entails some serious risks. One of the risks is undermining the environmental integrity of the carbon pricing scheme when low quality, nonadditional or overestimated offsets are used for compliance. Additionally, another relatively less important risk is that emission reduction efforts shift to other sources outside the carbon pricing scheme. Depending on the scale to which offsets are allowed and used, investments in emission reduction may permanently be diverted away from emissions sources covered by the compliance scheme generating carbon lock-in effects [80].
Furthermore, introducing an offset component may generate opposition to further climate policies.

Because of these risks, as existing systems mature and new ETSs are implemented, the focus seems to be increasingly turning to offsets within domestic borders, where these risks can be mitigated, and appropriate policies and countermeasures be put in place. This seems to be a general trend, although it is especially clear among developing countries. Though many systems in developed regions, such as in Europe and some in the US, have moved (or stayed) away from international offsetting provisions or offsetting entirely, some carbon pricing schemes may continue to use international offsets to leverage mitigation opportunities outside their borders and find a balance between the benefits of using offsets and the need to ensure domestic and intra-ETS abatement.
The major criticism of offset use in ETSs is around environmental integrity and whether they allow polluting sectors a way out of their obligations rather than taking concrete action to decarbonize themselves. Furthermore, for long-term decarbonization strategies, there is increasing interest in the role of carbon removals, which could be integrated into ETSs and Carbon Taxes through offsetting provisions. Finally, offsets traditionally used in voluntary markets, such as those stemming from independent standards like Gold Standard and VCS, are increasingly being considered to fulfil obligations in compliance carbon pricing instruments worldwide. Though not yet the case in any operational ETS, this is possible in the future. While the use of units from independent standards reduces administrative burden, it requires standardization and ensuring environmental integrity [77].

3.7.2 Voluntary carbon offsets price

Because a unit of GHG reductions have the same effect wherever they take place, according to the law of one price, it could be expected offset prices to converge to a same value. Nevertheless, the price of carbon offsets is highly variable [81].

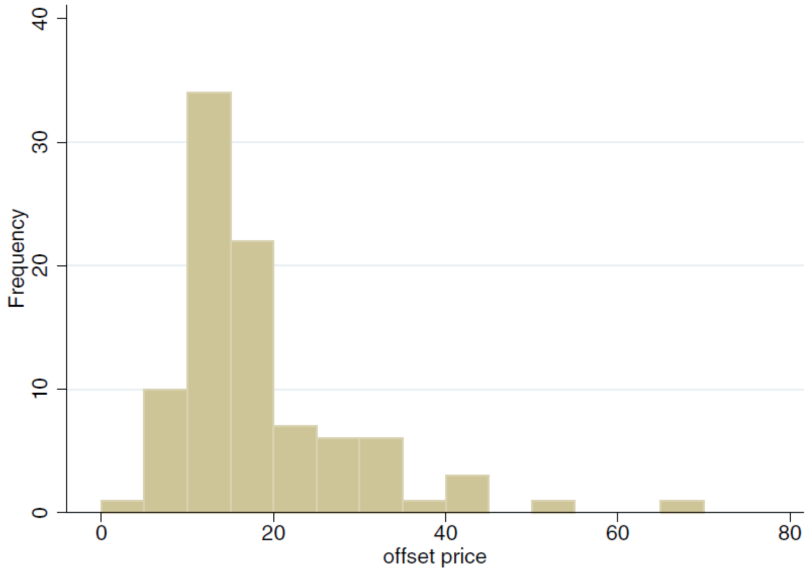


Fig. 3.20 – Histogram of carbon offset prices ($2007s/$CO_2$eq) for providers listed on Carbon Catalog in 2007 [81].

This fact has been reported since the early stages of the market, as shown in **Fig. 3.20** showing the price of carbon offsets prices for providers listed on Carbon Catalog in 2007 [81]. Conte et al. [81] estimated hedonic price functions focusing on characteristics of the offsets and of their providers to help explain this price variability. The authors found evidence that providers located in Europe sold offsets at prices that were at a premium (of around 30%) compared to providers located in either North America of Australasia. A possible interpretation proposed by the authors suggests that this might be due to higher awareness about climate change and agreement to take action in Europe than in the rest of the world at the time. Results also highlighted a (roughly 20%) higher price for projects located in developing and least-developed nations, possibly associated with a desire for wealth redistribution and poverty alleviation. Additionally, forestry-based projects, although popular and often presenting associated co-benefits, sold for substantially lower prices than offsets of other types of projects especially when located in non-industrialized countries. According to the authors this difference might have reflected the uncertainty related with these projects and the lack in developing nations of the institutions required to certify the quality of offsets. The authors concluded that although their findings were robust, the carbon offset market was still relatively new and possibly lacking sufficient competitive pressure to cancel price differences.

However, despite being more mature, similar differences also present in 2015 (as shown in **Fig. 3.21**) according to Gold Standard and 2022 (**Fig. 3.22**). According to Abatable [82] the offsets prices differences in 2022 were explained by similar reasons as those advanced by Conte et al. [81], including:

- Project type considerations like the development cost;
- Vintages: Carbon credits with older vintages are currently valued lower on the market;
- Removals vs avoidance: removal credits are currently available in structural under-supply relative to avoidance carbon credits, hence removal credits often command a premium relative to avoidance credits;
- Co-benefits: Projects which have additional social and environmental certifications like the CCB or SDVista certifications command a premium;
- Developer quality and reputation;
- Region/country: Some credits located in developed economies may command a premium reflecting corporates' preference to back projects closer to their business operations. Additionally, the interaction between the voluntary and compliance markets in some countries like the United States may drive a level of price convergence which may not be possible in other regions;
- Wholesale vs retail prices;
- Volume.

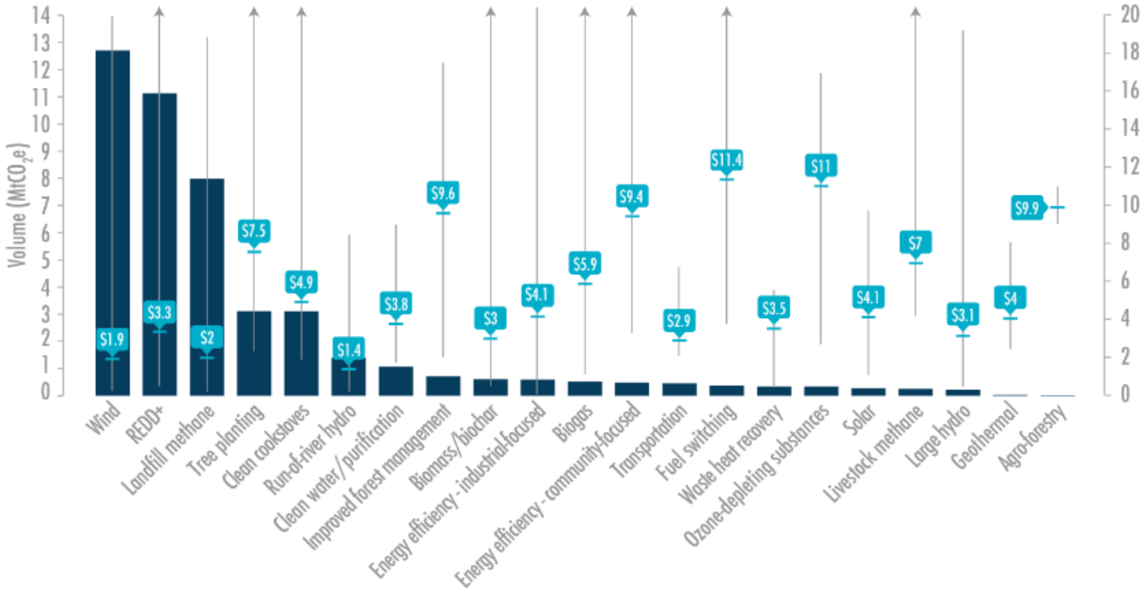


Fig. 3.21 – Transacted offset volume, average price, and price range by project type, 2015, Gold Standard Market Report [83].

Fig. 3.22 – Average price and price range by project type, 2022, Abatable [82].

Concerning price evolution, according to data from Ecosystem market place [84] in 2022 prices reached an all-time high global volume weighted average price of $7.37 per ton of CO_2eq, which just slightly beats the previous market record, set in 2008 when average prices hit $7.34 per ton when traded volumes were roughly half of the 2022 values ((123.4 $MtCO_2$eq and $704.8 Million in 2008 compared to 254,084,605 and $1,873,151,444 respectively in 2022).

However, prices have been slumping in 2023 according to S&P Global [85] particularly due to quality concerns. It's also worth noting that demand for carbon credits so far has been relatively low leading to a 'race to the bottom' for sellers to be able to sell their carbon credits (some vintage credits are decades old), leaving the average cost of carbon low overall.

Despite these concerns, demand is expected to grow as more and more individuals and businesses start to address their carbon footprint. McKinsey, for instance, estimates a 15x growth in demand by 2030 [86] which should result in a higher average cost of carbon. According to the study, developing standardized contracts and consolidating trading activity around a few types of contracts could promote liquidity and generate reliable price signals.

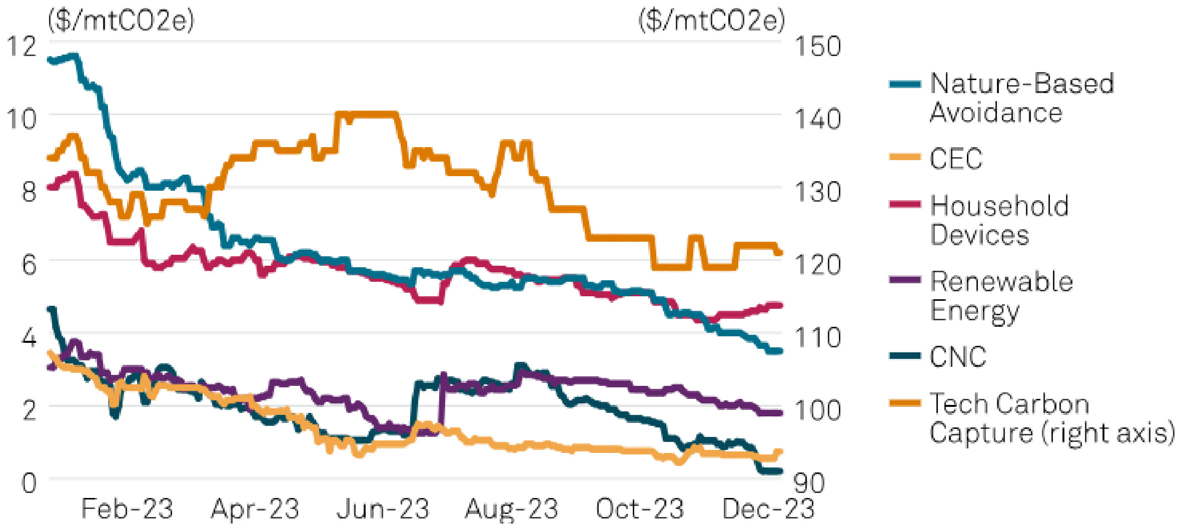


Fig. 3.23 –Offsets prices across segments in 2023. S&P Global Commodity Insights [85].

3.8 Conclusions

The system of international climate agreements has significantly shaped environmental policy, particularly regarding emissions reductions. The Kyoto Protocol marked a significant milestone by establishing binding emission reduction targets among industrialized nations, fostering collaborative mechanisms like International Emission Trading and Clean Development Mechanism. Despite its limitations, particularly in covering a relatively small portion of global emissions, it laid the groundwork for subsequent frameworks. The Paris Agreement, succeeding Kyoto, marked a shift towards a universal commitment to combat climate change. Unlike its predecessor, it mandated action from all countries, setting nationally determined contributions as binding commitments subject to monitoring and reporting. It also introduced cooperative approaches, continuing the legacy of flexible mechanisms while providing room for interpretation and ongoing negotiations.

Carbon offset markets, categorized into mandatory and voluntary programs, as well as Cap and Trade or Baseline and Credit systems, offer mechanisms for emissions reduction. Cap and Trade systems, defining emissions limits and tradable allowances, provide certainty and cost-effectiveness, while Baseline and Credit systems incentivize emission reduction beyond stipulated levels. However, challenges persist in verifying the "additionality" of reductions and potential overlaps with other emission-limiting tools.

The current status of carbon pricing systems highlights an increasing worldwide diffusion, proving that these schemes can be an effective tool to reduce carbon emissions. The European Union's adoption of a Cap-and-Trade structure, exemplified by its EU ETS, underscores the system's flexibility, capability of revenue generation, and risk reduction for member state budgets and emerges as a pivotal case study having influenced the development of similar ETSs around the world. According to researchers, that the EU ETS saved about 1.2 billion tons of CO_2 between 2008 and 2016 (3.8% of total EU-wide emissions) relative to a world without carbon markets, or almost half of what EU governments promised to reduce under their Kyoto Protocol commitments. These reductions also seem to have had little impact on the economic performance of covered companies so far, although allowances prices have been very low until recently and the effect of increasing prices is yet to be assessed. This might pose a risk of carbon leakage, i.e. companies relocating their production abroad to reduce their costs. The magnitude of the phenomenon has been so far contained, the EU has already devised preemptive measures and tools like the CBAM. Presently, no mechanism for integrating CO_2 removal credits (CRCs) into the EU ETS framework exist (which would enable more ambitious net emissions reduction targets), and a direct link between emitting activities and the use of emissions-reducing technologies must exist

Unlike compliance markets, voluntary market, which operate independently from them and in which companies can decide to participate on a voluntary basis, allow for the accounting of carbon removal and offer further sectorial and geographical flexibility. Additionally, they allow to integrate various co-benefits in addition to the simple CO_2 reductions. However, voluntary carbon markets have so far been characterized by lack of information and of critical analyses. For this reason, the need for quality assurance in order to maintain the credibility of voluntary offsets in the absence of government oversight is evident and the issue has recently been the object of public scrutiny. Despite these concerns, a 15-fold demand increase is expected as more and more individuals and businesses start to address their carbon footprint.

Overall, these international agreements and market mechanisms can and will play pivotal roles in mitigating climate change. They provide frameworks for collective action, but ongoing negotiations and enhancements remain imperative to effectively reduce global emissions and combat the challenges posed by climate change.

Chapter 4

The market of Biofuels

The shift from fossil fuels to renewable energy sources to decarbonize the transportation sector presents several challenges. In this context, biofuels can play a pivotal role. Biofuels offer a low-carbon alternative for current transportation technologies but face technological barriers in achieving properties similar to those of fossil fuels, and sustainability concerns regarding raw material sourcing. Despite these challenges, biofuels are positioned as a critical component in achieving Net Zero Emissions, as evidenced by the anticipated growth in demand. Governments play a crucial role in fostering biofuel adoption through regulatory frameworks, sustainability standards, and financial incentives. However, economic fluctuations and geopolitical influences impact the biofuel landscape, necessitating adaptable and robust implementation strategies.

4.1 Introduction

One of the distinguishing features of our society compared to those of a not-too-distant past is the high mobility of people and goods, leading to substantial energy consumption in the transportation sector. According to the IEA [87], energy consumption in the transportation sector (the majority of this was covered by fossil fuels) in 2022 accounted for approximately one quarter of world CO_2 emissions, i.e., about 8 $GtCO_2$.

In order to progress towards a significant decarbonization of our society, it’s imperative to gradually replace fossil fuels with renewable energy sources. Decarbonizing transportation is more challenging compared to other sectors like electricity production. This is because fossil fuels like gasoline, diesel, and kerosene possess certain characteristics that make them highly suitable for powering vehicles, ships, and aircraft. Specifically:

- Their high energy content, greater than any other commonly used chemical product, ensures considerable range for transportation (hundreds or thousands of kilometers) with a single refueling.
- The ease of standardizing their chemical and physical properties enables their use across all land, air, or sea motorized vehicles in any country worldwide.
- Their wide availability and relatively moderate costs, usually lower than potential alternatives.

Excluding potential supply issues linked to geopolitical crises (wars and market tensions), replacing fossil fuels with renewable sources poses a significant challenge. It needs to be approached with the understanding that there's no optimal solution; rather, it's crucial to identify realistically feasible options as they emerge. With current technology, several alternatives exist, ranging from electric propulsion vehicles (powered by renewable electricity) to synthetic fuels derived from various renewable sources other than biomass or from non-renewable waste not usable for material recovery, including the use of biofuels.

European legislation (Decree 28/2011) defines biofuels as "liquid or gaseous fuels for transportation derived from biomass," covering a broad range of products with significantly different characteristics. In practice, only a limited number of biofuels are industrially produced and introduced to the market: biodiesel, a blend of chemically modified esters from vegetable and/or animal oils and fats, ethanol and some of its synthetic derivatives (ETBE and other ethers), bio-hydrocarbons derived from the hydrogenation of oils and fats (HVO) or by-products of wood processing (tall oil), and, to an small extent, pure vegetable oils primarily used for agricultural machinery. Additionally, there's biomethane obtained through the purification (upgrading) of biogas used as a substitute for methane as compressed (LNG liquefied gas (bio-LNG). It's particularly applicable to local public transportation or long-distance freight transport via trucks and potentially valuable for non-electrified railway engines or inland/coastal navigation.

A broader and more widespread use of biofuels compared to current levels still requires overcoming certain challenges, which can be attributed to two main issues:

- Environmental concerns related to the nature and sourcing of the raw material (biomass) used in biofuel production.
- Technological challenges associated with the varying degrees of similarity, in terms of characteristics and properties, between biofuels and conventional reference fuels.

Regarding the first point, the goal is to progressively replace commonly used biofuels, known as "first-generation" biofuels, derived from agricultural raw materials (oilseeds, palm, corn, sugarcane, etc.), with more sustainable alternatives. These alternatives aim to avoid the risk of potential competition for land use with food and/or feed production.

The RED II (see Section 4.2) officially introduced the term "advanced biofuels" to encompass all liquid or gaseous biofuels obtained from agricultural and agro-industrial waste and residues, lignocellulosic biomass, algae, and specified residual biomasses (Annex IX). The primary distinguishing factor between a conventional biofuel and an advanced one is the raw material used for its production, regardless of the production technology and characteristics. A notable example of advanced biofuels is found in what's known as "second-generation" bioethanol, derived from lignocellulosic biomass rather than starch or sugar-based agricultural raw materials. This bioethanol is produced through an enzymatic hydrolysis process followed by the fermentation of the hydrolysates. In recent years, several industrial facilities have become operational for producing this biofuel, and numerous others are either under construction or in initial phases.

On the other hand, technological challenges stem from the chemical and physical properties of biofuels, which determine their similarity to or deviation from fossil-based products they aim to replace. Traditional biofuels differ chemically from hydrocarbons due to oxygen content, deteriorating their qualities and causing compatibility issues when blended with fossil fuels (the so-called "blending wall"). Hence, existing regulations set maximum blending ratios for fuels distributed through road networks, which may be surpassed in cases of off-network distribution like public transportation or waste collection.

This challenge intensifies notably in aviation when considering the use of biofuels. Traditional biofuels (biodiesel, ethanol, and derivatives) fail to meet stringent specifications for jet fuel, such as viscosity at low temperatures. Therefore, replacing jet fuel necessitates a new kind of biofuel, termed "drop-in" fuel, i.e., liquid hydrocarbons obtained from biomass with chemical and physical properties akin to fossil fuels and fully compatible with existing engines, storage, transportation, and distribution infrastructure.

Transforming biomass-derived products (like vegetable oils, fats, alcohols, pyrolysis oils, etc.) into a mix of hydrocarbons requires oxygen removal to achieve a hydrogen-to-carbon ratio as close as possible to the value of 2, typical of diesel and jet fuel. Similar to refinery processes where crude oil undergoes treatment with hydrogen to remove sulfur, oxygen, and other heteroatoms (hydrotreating) and "crack" long-chain hydrocarbons, producing drop-in biofuels necessitates hydrogen input which grow the higher the oxygen content to be removed.

Drop-in biofuels can be derived from various raw materials, employing processes and technologies at different developmental stages. Technologies for producing drop-in biofuels from fatty acid esters, vegetable oils, or hydrotreated tall oil (HEFA or HVO) are presently the only ones industrially developed, yielding significant, though still limited quantities of renewable fuels (SAF - Sustainable Aviation Fuels) viable for aviation transport. The associated processes are complex, costly, and heavily reliant on economies of scale. Consequently, industrial implementations are confined primarily within refineries (or biorefineries).

In the coming years, a substantial increase in electricity consumption from renewable energy sources is anticipated in public and private road transport. However, for decarbonizing transport systems requiring high energy density to cover extensive distances (primarily aviation but also maritime and long-haul road transport with heavy vehicles) there are presently no practical alternatives to liquid biofuels.

From this perspective, drop-in biofuels, derived from low-cost raw materials that are abundantly available and easily accessible, particularly those not competing for land use or consumption with food or feed production, will become increasingly important. A meticulous cost-benefit assessment, considering all technological, economic, and environmental aspects of various potential solutions, coupled with advancements in research, will form the fundamental basis for substantial and enduring growth in the market for this new generation of biofuels and will contribute to addressing the sustainability challenge for future transportation.

4.2 Policies and frameworks

As previously highlighted, although global demand for biofuels is growing accompanied by increase in production, this growth doesn't align with the pace outlined in the Net Zero Scenario. Governments have the opportunity to utilize various regulatory tools like mandates, low-carbon fuel standards, and greenhouse gas intensity targets, alongside strategies such as carbon pricing and financial incentives, to boost biofuel demand. It's essential that these policies consistently incorporate strict sustainability criteria and actively encourage reductions in greenhouse gas emissions.
Government programs and policies can be broadly grouped into 3 categories: *Strategic Planning*, *Regulatory design* and *Financial support*. These policies and programs, in addition to historical efforts to date, are promoting an unprecedented level of new project development, and it is estimated that projects using unconventional feedstocks would more than triple existing production.

However, it is important to also note that the number of planned projects using unconventional feedstocks is not enough to avoid a feedstock supply crunch over the medium term according to the IEA [88]. Even if every proposed project is built on time, new production potential amounts to just 4% of existing biofuel production globally. Nevertheless, thanks to policies in major biofuel markets, these planned facilities have the potential to substantially increase the existing capacity of plants utilizing non-traditional feedstocks by 2030 [88].
Governments and companies have four main options to alleviate feedstock constraints while increasing sustainable biofuel production:

- Enhance output from current feedstocks through increased crop cultivation, supply chain investments, and improved collection of waste and residues.
- Expand crop production to regions without competition from food or feed crops.
- Employ biofuel technologies capable of processing alternative feedstocks like woody organic residues.
- Lower the GHG intensity of fuels, enabling emission reduction goals to be achieved with reduced biofuel volumes.

Although the number of upcoming projects is considerable, it's currently insufficient to prevent a potential shortage in feedstock supply. However, these projects might serve as a foundation for rapid deployment if successful models are showcased, and if economies of scale are established. Rising feedstock prices, signaling scarcity, could encourage investment in new supplies. Moreover, many alternatives don't need constructing new facilities but rely on accessing new feedstocks or adjusting existing plants. This suggests that change could happen swiftly with appropriate incentives [88].

Sustainability frameworks

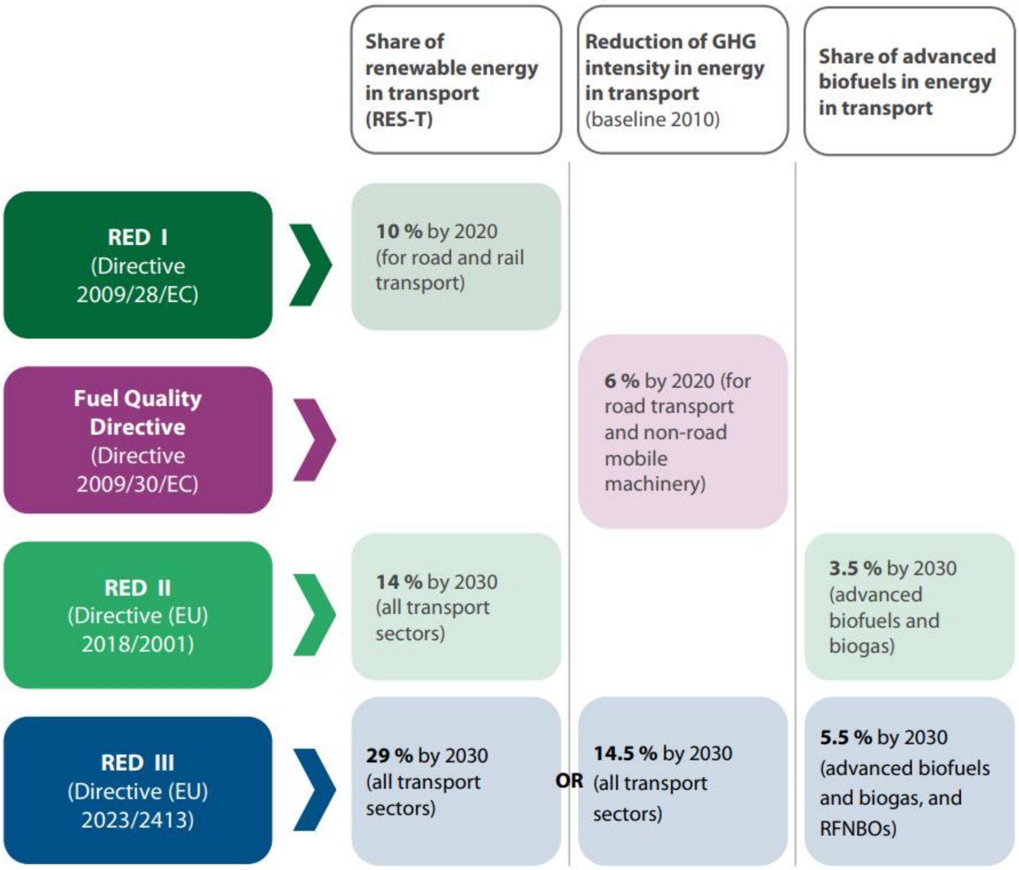
Ensuring the positive impact of increased biofuel consumption requires robust sustainability governance, emphasizing social, economic, and environmental benefits, notably reductions in life cycle greenhouse gas emissions. Policymakers play a crucial role in establishing frameworks to support only those biofuels meeting stringent sustainability criteria, validated through third-party certification of biofuel supply chains.
The European Union (through requirements in its RED-Renewable Energy Directives), the United States (through minimum GHG thresholds in the federal RFS program and the incorporation of indirect land-use change into the state of California’s LCFS) and Brazil (through its RenovaBio program) have established frameworks to codify some aspects of biofuel sustainability, but other countries must also ensure that rigorous sustainability governance is linked to biofuel policy support.
Furthermore, governments should introduce policies that aim to reduce the lifecycle carbon intensity of fuels (such as California’s Low Carbon Fuel Standard). Advanced fuels with lower carbon intensities are rewarded financially under such policies.

Food security is also top of the agenda for many governments, but to date only Belgium and Germany are considering relaxing biofuel mandates to address this issue, also in consideration of the fact that better tools to address food security concerns might exist. The FAO has recommended measures to manage high prices, emphasizing diversified food supplies and supporting vulnerable groups. Nevertheless, China has warned ethanol producers that it will "strictly control processing of fuel ethanol from corn" and the European Union Commission has noted it will support member states that reduce mandates in the name of food security.

Governments face a delicate balance in reducing mandates, recognizing that any decline in biofuel demand might result in increased oil deliveries and greenhouse gas emissions, conflicting with their sustainability priorities. Consequently, adjustments to mandates are likely temporary, aimed at addressing immediate challenges while maintaining long-term objectives. For instance, Finland relaxed short-term targets while simultaneously boosting the long-term blending target for 2030.

European Renewable Energy Directives (RED, RED II, RED III)

Over the years, the European Commission has implemented various strategies concerning transportation and biofuels. These strategies, starting from 2009, became incorporated into the initial Renewable Energy Directive (RED), and in subsequent years, were further refined in RED II [89], which was revised in 2023 alongside introducing the RED III (**Fig. 4.3**).



	Share of renewable energy in transport (RES-T)	**Reduction of GHG intensity in energy in transport** (baseline 2010)	**Share of advanced biofuels in energy in transport**
RED I (Directive 2009/28/EC)	**10 %** by 2020 (for road and rail transport)		
Fuel Quality Directive (Directive 2009/30/EC)		**6 %** by 2020 (for road transport and non-road mobile machinery)	
RED II (Directive (EU) 2018/2001)	**14 %** by 2030 (all transport sectors)		**3.5 %** by 2030 (advanced biofuels and biogas)
RED III (Directive (EU) 2023/2413)	**29 %** by 2030 (all transport sectors)	**OR** **14.5 %** by 2030 (all transport sectors)	**5.5 %** by 2030 (advanced biofuels and biogas, and RFNBOs)

Fig. 4.1 – Biofuel related targets [90].

Concerning the aviation and maritime sectors, ReFuelEU Aviation and FuelEU Maritime were adopted in 2023 (**Fig. 4.2**). ReFuelEU Aviation mandates all fuel providers at EU airports to have a minimum percentage of Sustainable Aviation Fuels (SAF), which are low-carbon substitutes for kerosene derived from recycled carbon or synthetic fuels. The minimum SAF percentage must increase from 2% in 2025 to 70% by 2050. Regarding maritime transport, the objective is to gradually encourage shipping operators to replace fossil fuels with low-carbon alternatives. Unlike ReFuelEU Aviation, FuelEU

Maritime does not specify the proportion of specific fuels to be used. Instead, it sets a target for reducing the intensity of fossil energy used on board, aiming for at least a 2% reduction by 2025 and up to 80% by 2050 compared to 2020 levels.

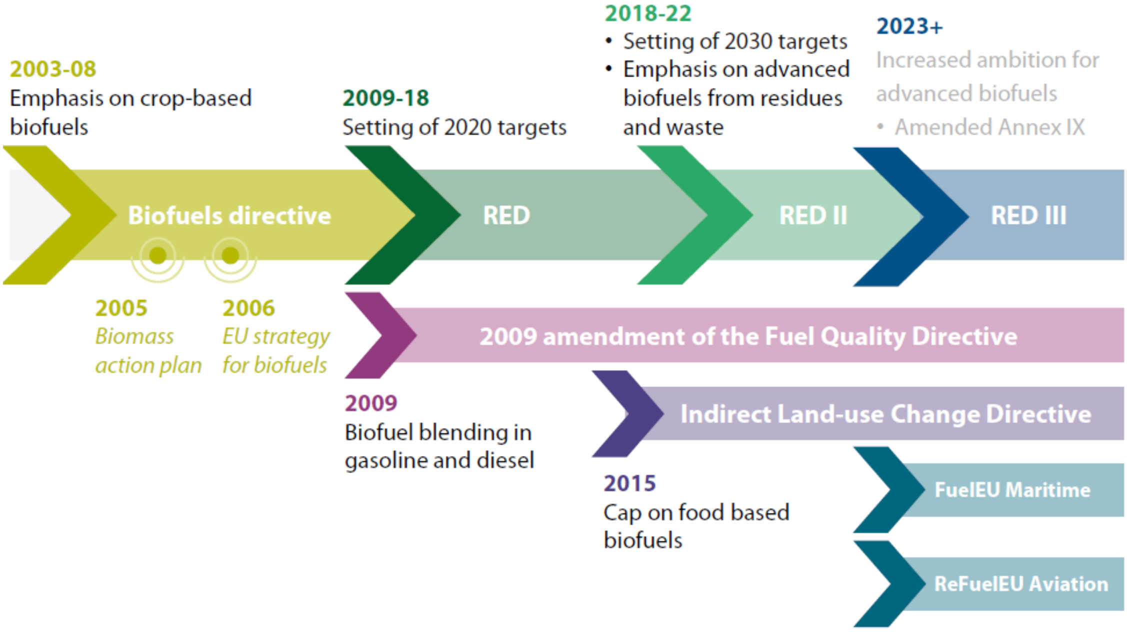
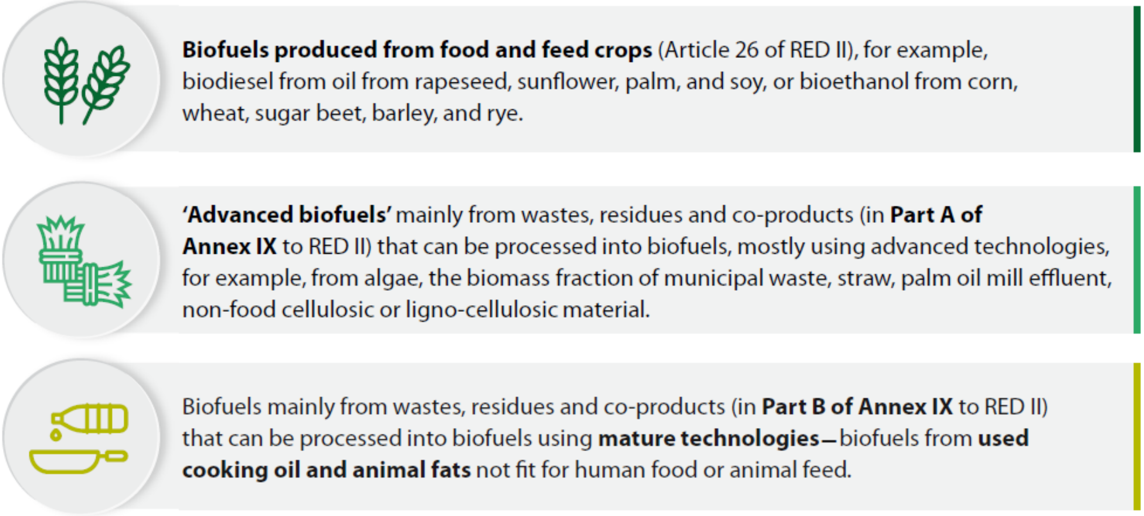


Fig. 4.2 – Key developments in EU policy for biofuels [90].

Among the various types of biomasses that can be used for biofuel production, the 'RED II' directive distinguishes three main categories based on the raw material or technology used: biofuels from food and feed crops, advanced biofuels and biofuels from wastes, residues, and co-products (**Fig. 4.3**). For the latter two, RED II contains a list of specific raw materials and groups of raw materials. Biofuels that do not use any of the raw materials included in the three categories are defined as 'other biofuels' and include, for example, biofuels derived from non-food crops or forage such as Jatropha, or from textile crops such as flax or hemp.



Biofuels produced from food and feed crops (Article 26 of RED II), for example, biodiesel from oil from rapeseed, sunflower, palm, and soy, or bioethanol from corn, wheat, sugar beet, barley, and rye.

'Advanced biofuels' mainly from wastes, residues and co-products (in **Part A of Annex IX** to RED II) that can be processed into biofuels, mostly using advanced technologies, for example, from algae, the biomass fraction of municipal waste, straw, palm oil mill effluent, non-food cellulosic or ligno-cellulosic material.

Biofuels mainly from wastes, residues and co-products (in **Part B of Annex IX** to RED II) that can be processed into biofuels using **mature technologies**—biofuels from **used cooking oil and animal fats** not fit for human food or animal feed.

Fig. 4.3 – Main categories of biofuels by feedstock [90].

As mentioned, despite their potential to reduce greenhouse gas emissions, biofuels could also have a negative impact on the environment and climate, affecting biodiversity, soil, water, and competing with food production. To mitigate the risks of adverse effects on the environment and climate, the RED II sets various sustainability criteria for biofuels, which are considered "sustainable" only if they meet all the following criteria [90]:

- Agricultural feedstock must not be obtained from:
    - land with a high biodiversity value;
    - land with high carbon stock;
    - land that was peatland in January 2008.
- Forest biomass must be backed-up by evidence on mechanisms ensuring:
    - the legality of the harvesting operations
    - forest regeneration of harvested areas;
    - protection of designated nature protection areas, including wetlands and peatlands;
    - harvesting maintains or improves soil quality, biodiversity, and the long-term production capacity of the forest.
- The GHG savings from the use of biofuels compared to fossil fuels should be:
    - at least 50% if biofuel is produced in installations in operation on or before 5 October 2015;
    - at least 60% if biofuel is produced in installations starting operation from 6 October 2015 until 31 December 2020;
    - at least 65% if biofuel is produced in installations starting operation from 1 January 2021;

Concerning the last point RED II includes a formula for calculating the GHG emissions savings from biofuels, to be used by the member states when operators place biofuels on the market:

$$Total\ emissions = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} \tag{4.1}$$

Where:

- e_{ec} are the emissions from the extraction or cultivation of raw materials;
- e_l are annualized emissions from carbon stock changes caused by land-use change;
- e_p are the emissions from processing;
- e_{td} are the emissions from transport and distribution;
- e_u are the emissions from the fuel in use;
- e_{sca} are the emission savings from soil carbon accumulation via improved agricultural management;
- e_{ccs} emission savings from CO_2 capture and geological storage;
- e_{ccr} are emission savings from CO_2 capture and replacement.

International collaboration on biofuels

International collaboration can help accelerate biofuel deployment by developing best practices, coordinating research, policy, and deployment, and promoting common sustainability standards. Examples of international collaboration initiatives on biofuels include:

- The Biofuture Platform Initiative: a 22-country initiative to promote an advanced low-carbon bioeconomy that is sustainable, innovative, and scalable, established under the Clean Energy Ministerial in 2021. It aims to foster consensus on biomass sustainability, promote best practices, enable financing, and promote international cooperation.
- IEA Bioenergy: a Technology Collaboration Programme (TCP) established in 1978 to facilitate cooperation and information exchange between countries that have national programs in bioenergy research, development, and deployment. It provides leading analysis on bioenergy technology development, demonstration, market deployment, sustainability, and policy frameworks.

- Global Bioenergy Partnership: an initiative focusing on developing countries to support a range of activities including national and regional policy making and supporting sustainable practices. This includes the development and implementation of 24 sustainability indicators.
- Clean Skies for Tomorrow Coalition: an industry-led coalition working to advance the commercial sale of viable, low-carbon sustainable aviation fuel (SAF) for broad adoption by industry in 2030.

4.3 Biofuels in the EU ETS

As discussed in Section 3.5, the ‘Fit for 55’ package, designed by the European Union to reduce the European Union's greenhouse gas emissions by 55% by 2030, accelerates the implementation of the polluter pays principle by phasing out free allowances for the aviation sector by 2026. This agreement increases the stringency of the existing system, which has covered aviation since 2012. Indeed, under the EU ETS, all airlines operating flights that depart and arrive within the European Economic Area (EEA) are required to monitor, report, and verify their emissions, and to surrender allowances against those emissions.

The deal also provides for a new support scheme to speed up the use of sustainable aviation fuels, financed with EU ETS revenues which are estimated at €1.6 billion. The EU ETS provides an incentive for airlines to use SAF certified as compliant with the sustainability criteria of the Renewable Energy Directive (RED), by attributing them zero emissions under the scheme, thus reducing airlines’ reported emissions and the ETS allowances they need to purchase.

On January 1, 2024, the European Union expanded the scope of its ETS to encompass the maritime industry, as part of a broader reform of the EU ETS initiated in June 2023. This sector contributes approximately 3 to 4% of the EU's overall CO_2 emissions. Following this extension, the EU ETS now encompasses emissions from large vessels departing from or arriving at EU ports, irrespective of their flag. Initially, the regulations apply to ships transporting goods and passengers with a gross tonnage of 5’000 or more. By 2027, the coverage will be extended to vessels involved in offshore activities such as oil and gas exploration or maritime construction, also exceeding a gross tonnage of 5’000.

The system addresses emissions generated while ships are docked in EU ports and during their journeys within EU waters, with an additional inclusion of 50% of emissions from voyages to or from non-EU countries. Initially, the extended system focuses solely on CO_2 emissions, with plans to incorporate methane (CH_4) and nitrous oxide (N_2O) emissions from 2026 onwards.

Aligned with the principles governing other sectors within the EU ETS, shipping companies are obligated to actively monitor their emissions and obtain and surrender EU allowances (EUAs) corresponding to each ton of reported greenhouse gas emissions. This integration builds upon the existing EU Monitoring, Reporting, and Verification system established in 2015, marking a significant step toward pricing greenhouse gas emissions in the maritime sector.

Currently, also in the case of the Maritime sector, emissions resulting from the combustion of sustainable biofuels compliant with the sustainability criteria established by the Renewable Energy Directive have a CO_2 emission factor of zero under the ETS.

4.4 Current market and expected growth

Biofuels play a crucial role in reducing carbon emissions within the transport sector, offering a low-carbon solution for current technologies, particularly for light-duty vehicles in the short term and in the long term for heavy-duty trucks, ships, and aircraft, which have few alternative viable options.

The demand for biofuels reached 4.3 EJ (170’000 million liters) in 2022, surpassing 2019 levels after a decline during the Covid-19 pandemic and is expected to further grow in coming years (**Fig. 4.4**). However, according to the IEA [91], a substantial increase in biofuel production is necessary to align with the Net Zero Emissions by 2050 Scenario and achieve the associated emission target. To meet the

Net Zero Scenario by 2030, biofuel production must reach 10 EJ, requiring an average growth of approximately 11% annually. Moreover, there's a need for expanded usage of advanced feedstocks, such as biofuels derived from waste and residue resources, aiming to fulfill 40% of the total biofuel demand by 2030, a significant increase from the 9% share in 2021 [91].

Replacing fossil fuels with biofuels stands as a primary method for decarbonizing the transportation sector, constituting 64% of the sector's renewable energy consumption by 2030 in the IEA Net Zero Emissions by 2050 Scenario [92]. In this scenario, there's a growing shift towards producing biofuels from feedstocks like wastes and residues, which don't compete with food crops. By 2030, biofuels from these sources are anticipated to cover 45% of total biofuel demand, contrasting sharply with the estimated 7% derived from wastes and residues in 2020.
In 2021, biofuels only covered 3.6% of global transport energy demand, mainly for road transport, and are not yet on track to meet the trajectory for Net Zero, partly due to high commodity prices posing a near-term obstacle. Indeed, in the IEA Net Zero Scenario, this contribution quadruples to 15% by 2030, encompassing nearly one-fifth of fuel demand solely for road vehicles.

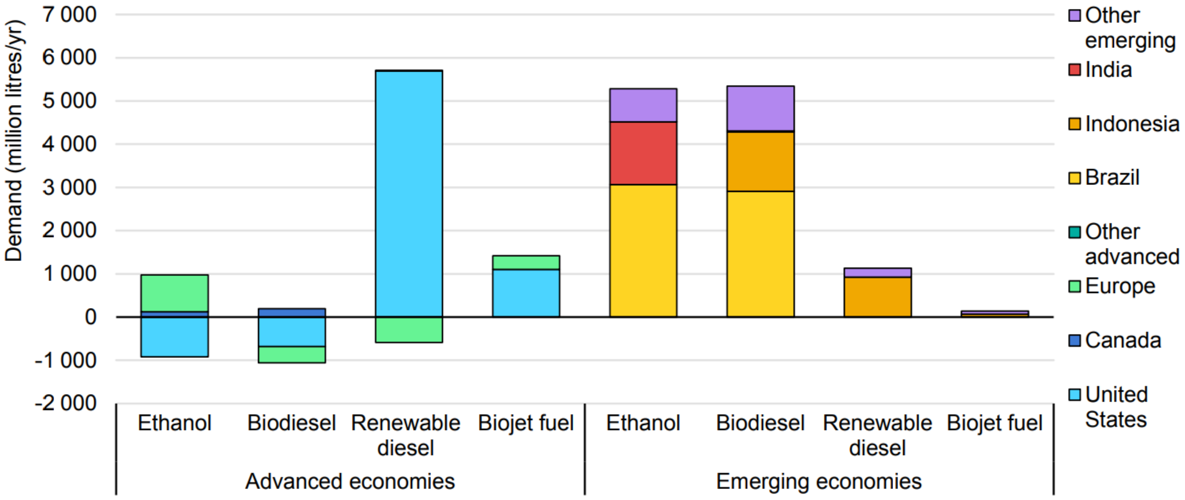


Fig. 4.4 – Biofuel demand growth by fuel and region, 2022-2024, IEA [88].

Aviation biofuels, referred to as biojet kerosene, need substantial advancement by 2030 to align with the Net Zero Scenario, increasing from 0.1% of aviation fuel demand in 2021 to over 5% by 2030. Achieving this depends on reducing cost differences between biojet fuel and fossil jet fuel, implementing clear regulatory frameworks by governments, and diversifying sustainable feedstock supplies beyond waste and edible oils.

As highlighted by the IEA, recent geopolitical events like the Russia-Ukraine conflict have strongly impacted energy and agricultural markets, significantly affecting biofuel demand growth projections. Indeed, geopolitical tensions have sparked shifts in global biofuel demand, shaping growth trajectories in major markets and prompting reconsideration of projections in light of evolving market dynamics.
Looking more specifically at the Italian situation, 31% of annual energy consumption, corresponding to 35 Mtoe, is attributed to transportation. Of this percentage fossil fuels like gasoline, diesel, kerosene, and LPG cover over 90%. This proportion has notably decreased (-26%) between 2005 and 2021. During the same period, the use of biofuels surged by 701%, increasing from 177 to 1,145 ktoe. More recently (from 2017 onward), biomethane has begun establishing itself, growing by 66% between 2020 and 2021, reaching nearly 140 ktoe in 2021. Presently, over 1.7 million tons of biofuels are consumed in Italy each year [93]. The majority consists of biodiesel (91%), totaling over 1,500,000 tons, followed by biomethane with nearly 117,000 tons, accounting for 7% of consumption. The contribution of bio-ETBE and ethanol remains marginal. Of the biofuels permitted for consumption, 86% fall under the "double

counting" category, i.e., derived from waste or residues, non-food cellulosic materials, and lignocellulosic materials which is double counted in the calculation of energy contribution. However, only 38.7% of this can be considered as "advanced," not competing with agricultural (no land use deduction) or food (not potential human or animal food) sectors.

Incentives and public resources have and will continue to expand the market base for biofuels. Italy has set ambitious targets in its PNIEC (National Energy and Climate Plan) fixing the renewable energy share in the transport sector at 22% by 2030, of which 38.6% must come from biofuels.
Moreover, the Italian national recovery and resilience plan (PNRR) allocated 1.7 billion euros to biomethane for investments via capital contributions and incentivizing tariffs for production. The objective is to promote a production capacity of approximately 2 billion cubic meters per year by 2024, ten times the current capacity.

These targets are, however, not always easy to reach. Considering RES-T targets for 2020 for example (**Fig. 4.1**), only seven member states have met their binding targets under RED I using solely biofuels and biogas (**Fig. 4.5**), while fifteen member states have not achieved their targets. Failure to meet binding targets may prompt the Commission to initiate an infringement procedure, potentially leading the Court of Justice to penalize a member state for failing to meet these objectives. However, despite the targets being binding under the Directive 2009/28/EC, as of May 2023 the European Commission had not yet started and infringement procedure [90].

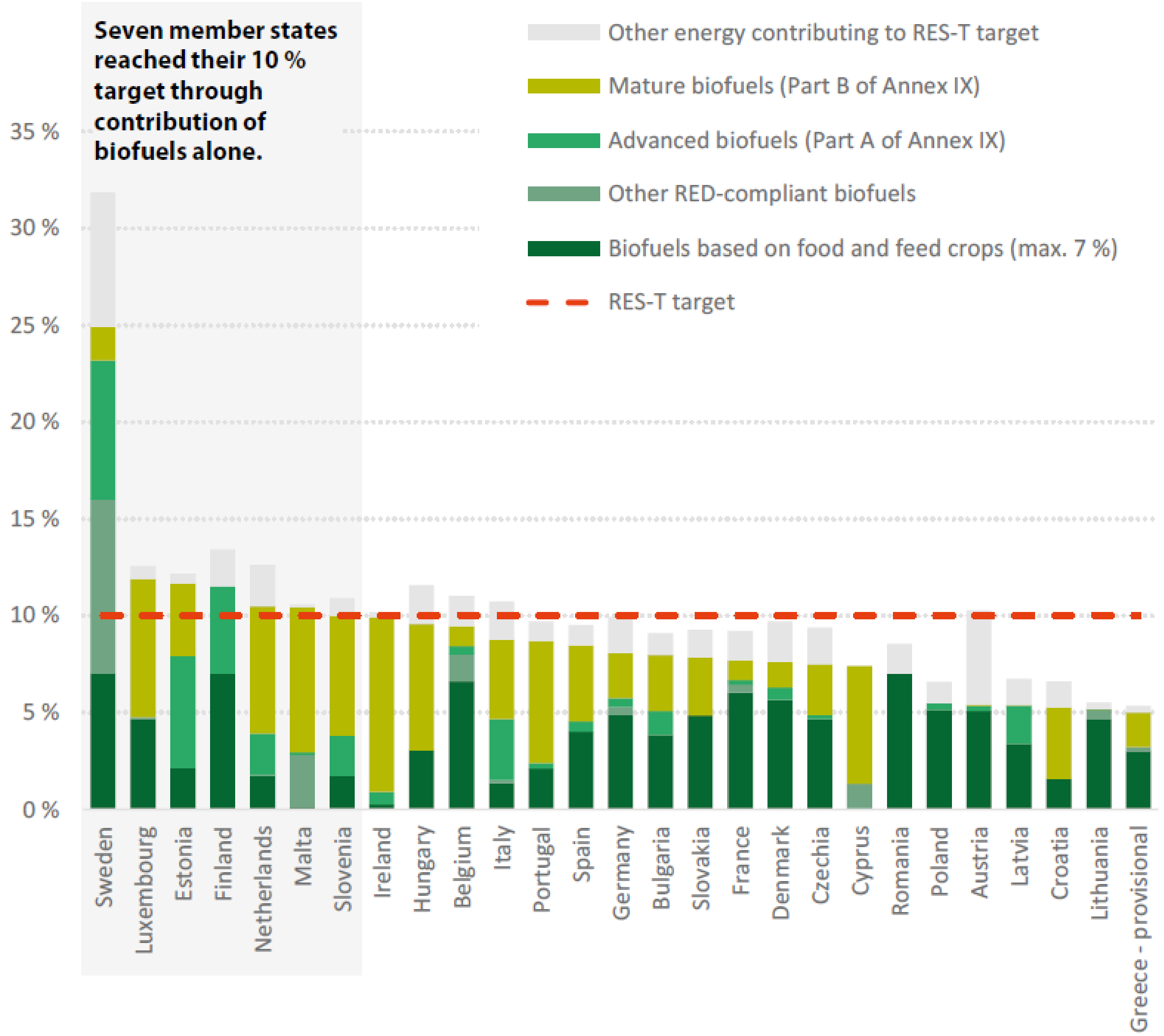


Fig. 4.5 – Contribution of biofuels to the 2020 target for renewable energy in transport (RES-T), with multipliers [90]. Note: in the figure biofuels also include biogas.

Additionally, despite intentions to transition towards advanced biofuels, in 2021, most biofuels consumed in the EU were still crop-based (**Fig. 4.6**). Renewable electricity and renewable liquid or gaseous fuels of non-biological origin (RFNBOs), are also carriers of renewable energy in transport. RFNBOs such as hydrogen are still emerging technologies.

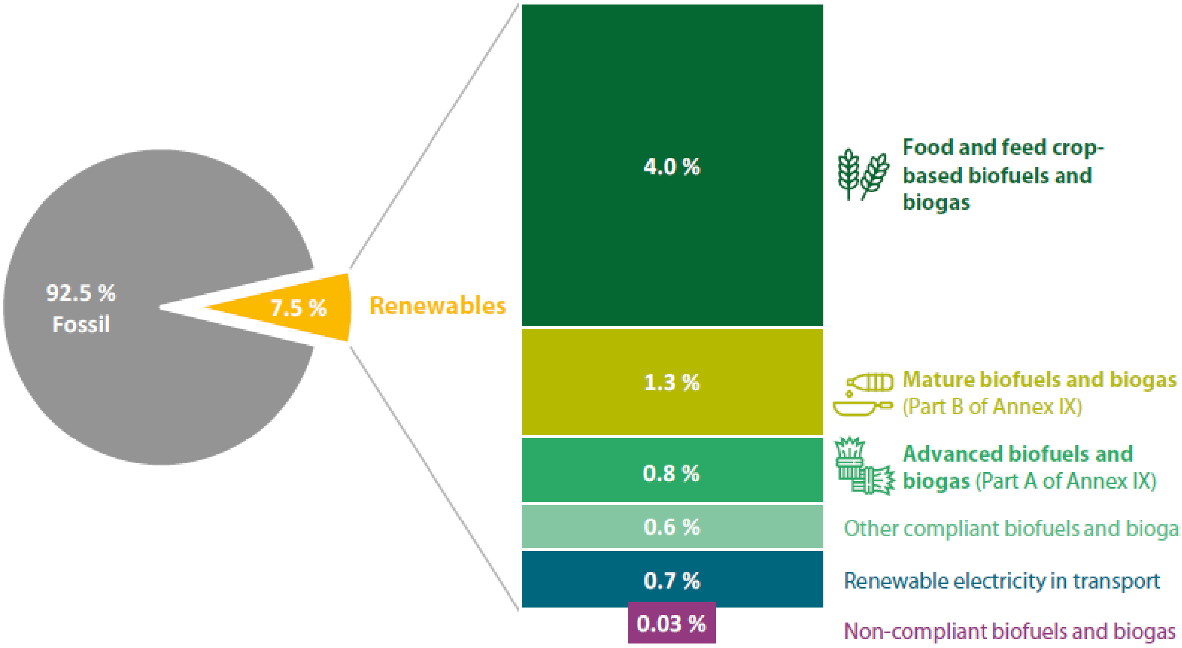


Fig. 4.6 – Energy mix in EU road and rail transport in 2021 [90].

4.4.1 Prices and costs

Following the peak in biofuel prices in 2022, a gradual decline ensued; however, projections indicate sustained price levels above those seen before the conflict in Ukraine. Biodiesel prices surged by up to 160%, while ethanol prices soared by as much as 75% from 2019 levels (**Fig. 4.7**), driven by a complex blend of factors such as trade disruptions, elevated energy prices, expensive fertilizers, and weather-related disruptions in primary biofuel feedstock supplies [88].

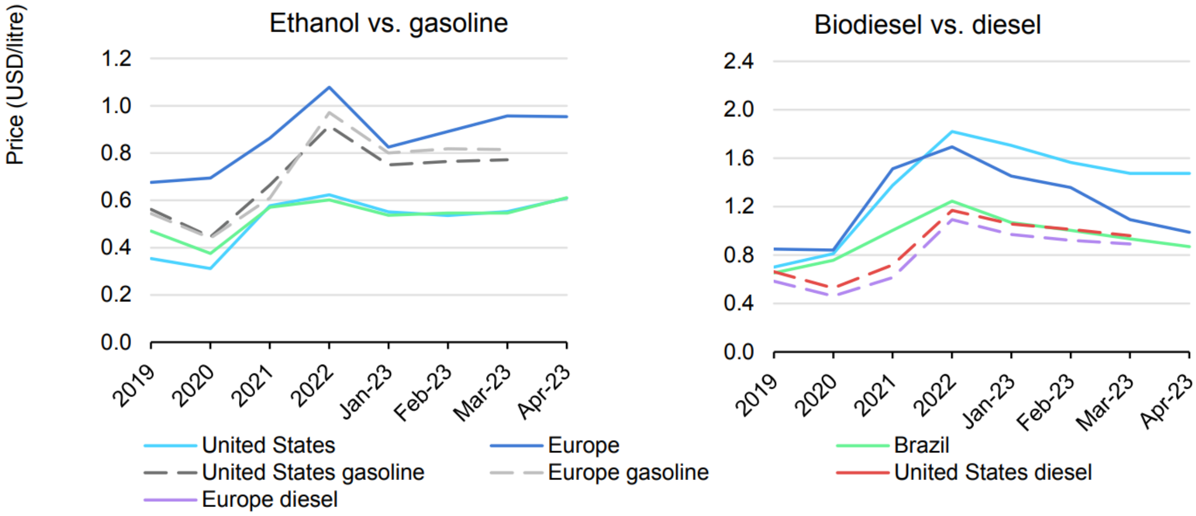


Fig. 4.7 – Ethanol and gasoline prices (left) and biodiesel and diesel prices (right) in selected markets, 2019-2023, IEA [88].

In the initial months of 2023, ethanol prices witnessed a decline of 7-16% from the 2022 average, paralleled by biodiesel prices dropping 15-28%, albeit varying across markets. Increased US ethanol prices are expected due to slightly higher-priced corn, the primary feedstock for ethanol production. Similarly, Brazil and India, confronted with decade-high sugar prices, might experience upward pressure on ethanol prices since both countries predominantly rely on sugar for ethanol production.

Despite a 27% decline from the record highs of 2022, vegetable oil prices for biodiesel production remain high, constraining the pace and scale of anticipated price decreases in the coming years. Concerns persist regarding Russia's invasion of Ukraine disrupting agricultural trade, impacting international markets. While biodiesel prices plummeted by over 40% since 2022 due to lower vegetable oil prices and increased imports of advanced biofuels and feedstocks, challenges remain. Notably, advanced biodiesel production from used cooking oil, tallow, palm oil mill effluent, and residues rises amid heightened imports, particularly from China, indicating an 18% increase in the first three months of 2023 [88].

The dynamics in the EU market, where each liter of advanced biofuel can count twice toward blending obligations, displacing conventional biodiesel, contribute significantly to declining prices. Ethanol, despite experiencing a decline from its 2022 peak, remains substantially above 2019 levels by 40%. High sugar prices, poor sugar beet harvests, and ongoing high input costs for natural gas and fertilizers collectively contribute to sustained higher ethanol prices. Nonetheless, ethanol demand is expected to surge by 12% to 8 billion liters by 2024, aligning with countries' commitments to biofuel obligations and greenhouse gas reduction targets in the transport sector.

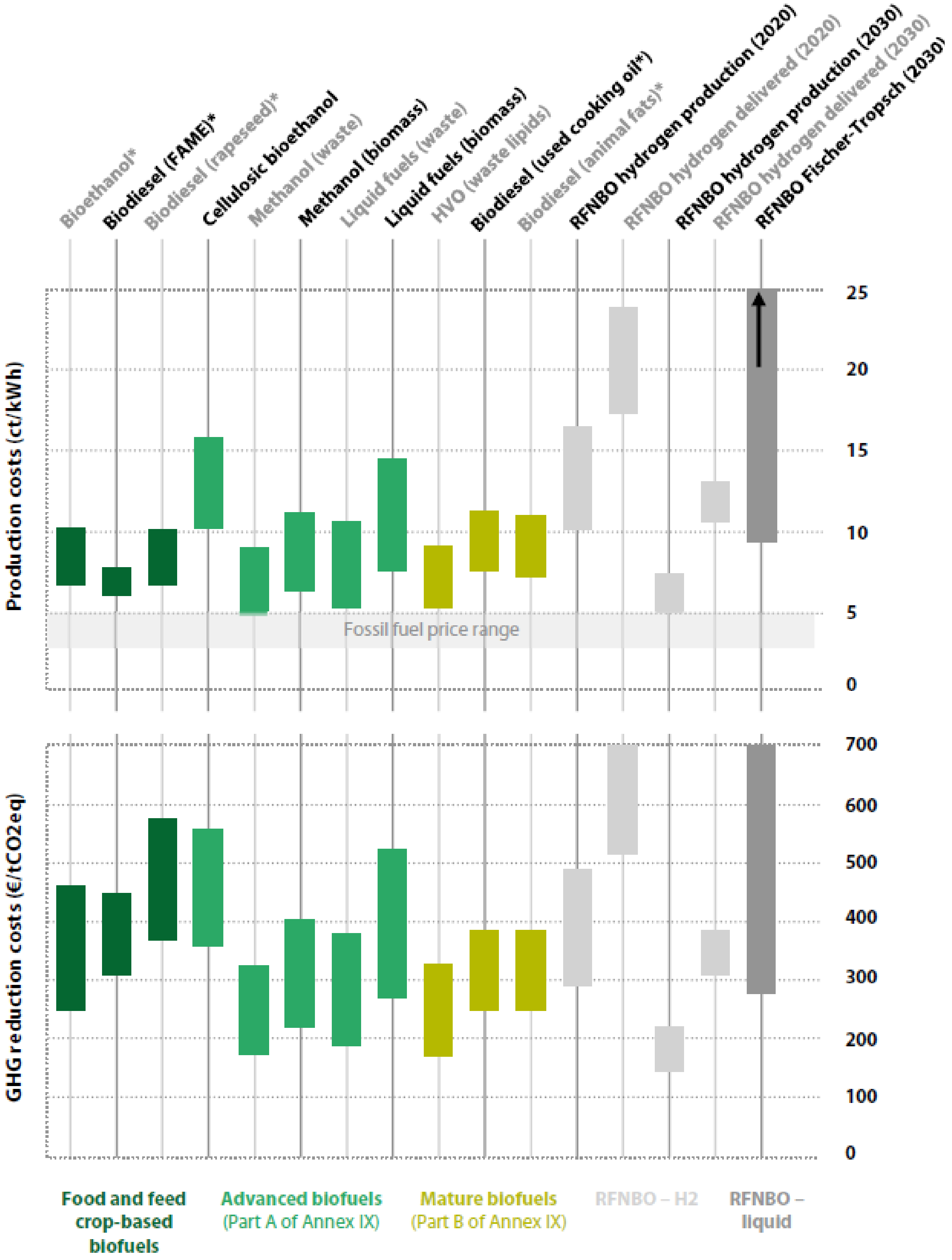
Forecasts suggest a slight decline in biodiesel prices in 2023/24 from their 2022 highs, attributed to decreases in vegetable oil prices, notably a 12% reduction in soybean oil costs compared to 2022. However, this decrease remains below the global average due to expanding renewable diesel production that boosts domestic demand while soybean oil supplies lag behind. Anticipated rising demand for renewable diesel might lead to a 75% reduction in exports as per the USDA's expectations for 2023.

Ethanol prices are anticipated to sustain their elevated status in 2023, because of a projected 9% drop in corn production coupled with stable demand, supporting a 10% increase in corn prices. Brazil's ethanol prices are forecasted to rise in response to higher international sugar prices and growing domestic demand. This scenario could favor ethanol produced from corn, representing 15% of Brazil's ethanol production, if production costs remain competitive compared to sugarcane ethanol.

Brazil's biodiesel prices, down by 30% from the previous year, anticipate a record soybean crop maintaining low prices. However, the raising of the country-s biodiesel blending mandate is expected to raise soybean demands, contributing to increased domestic demand. Brazilian soybean exports are forecasted to surge by 17%, compensating for a 60% year-on-year decline in Argentinian production due to droughts, prompting increased imports from Brazil by soy crushers in Argentina, the world's largest soymeal and soybean oil exporter.

By and large, biofuels price remains considerably higher than that fossil fuel counterparts, with the consequence that biofuel production and supply are driven by public policy rather than the market [94]. Generally speaking, production costs of biofuels vary depending on the production chain (**Fig. 4.8**). Biofuels generally have lower cost profiles compared to non-biological renewable fuels (RFNBO), especially in the short term. Advanced biofuels, which offer GHG emission reductions compared to crop-based biofuels, also entail lower GHG emission reduction costs than those derived from food crops.

The cost per ton of CO_2 reduction depends on the sector and the technology used; operators in transport subject to the Emissions Trading System are not obligated to use quotas for sustainable biofuels. This should help narrow the price gap with fossil fuels. However, ETS quotas prices have been very low until 2020 (**Fig. 3.9**), and even the picks reached in 2022 and 2023 of approximately 100 euros per ton of CO_2 are significantly lower than the cost of CO_2 emission reductions through biofuels, as depicted in **Fig. 4.8**, showing that unfortunately biofuels are yet not economically viable.



Note: Values marked with * are based on market price data.

Fig. 4.8 – Fuel costs/prices, and costs of GHG reduction [90].

4.5 Technologies

For most biomasses, multiple transformations are possible to obtain biofuels; the alternatives can be divided based on the type of raw materials and processes used and are characterized by different degrees of maturity.
Currently, most of the biofuel production relies on conventional feedstocks like sugar cane, corn, and soybeans. However, transitioning biofuel production toward advanced feedstocks is crucial to mitigate impacts on land use, food and feed prices, and other environmental aspects. In the envisioned IEA Net Zero Scenario, approximately 50% of biofuels consumed in 2030 will come from wastes, residues, and specific crops grown in non-competitive environments (e.g., crops cultivated on marginal land), a significant increase from the estimated 8% in 2021.

Presently, used cooking oil and waste animal fats contribute significantly to non-food crop feedstocks for biofuel manufacturing. As these resources are limited, the commercialization of new technologies becomes imperative to expand biofuel production from non-food crops. Technologies like cellulosic ethanol and others based on the Fischer-Tropsch process have the capacity to use non-food feedstocks, producing low-carbon biofuels applicable in the transportation sector.

Several biofuel production methods have attained commercial viability, including ethanol derived from corn and sugarcane, FAME biodiesel, HVO renewable diesel, and HEFA biojet (Hydroprocessed Esters and Fatty Acids) kerosene sourced from vegetable oils and waste oils. However, there remains an innovation gap in converting woody and grassy biomass into liquid biofuels, utilizing thermochemical paths like biomass gasification followed by bio-FT synthesis, hydrothermal liquefaction, and fast pyrolysis with upgrading. These routes tap into more abundant biomass waste and residue resources compared to HVO and HEFA, enabling renewable diesel and biojet kerosene to scale sustainably as required in the Net Zero Scenario.

While bio-FT is currently in the demonstration phase, several large-scale projects are in progress, predominantly in the United States but also in Europe and Japan. These projects encompass various feedstock options such as forestry residues and municipal solid waste, producing renewable diesel and biojet kerosene. One notable project, the Bayou Fuels biorefinery in the United States, plans carbon capture and storage for negative emissions, also known as carbon dioxide removal.

Hydrothermal liquefaction and fast pyrolysis with upgrading are at a lower technological readiness level than bio-FT, facing challenges in pre-treating bio-oils for further hydroprocessing into renewable diesel. However, once pre-treated, co-processing bio-oil with petroleum products (up to around 10%) at existing oil refineries can be a near-term solution, avoiding substantial capital expenditure related to scaling up. Presently, only a few pilot projects exist, such as the EU HyFlexFuel project and Sweden's Pyrocell, a collaboration between a sawmill and an oil refinery.

Several biofuel production methods inherently release a nearly pure CO_2 stream as part of their process [95]. These methods, including ethanol fermentation (both crop-based and cellulosic) and bio-FT, exhibit a high CO_2 concentration, resulting in low capture costs due to minimal additional purification, primarily dehydration. Since 2010, CO_2 capture has been practiced in ethanol plants, with initial projects selling the CO_2 for enhanced oil recovery or within the food and beverage sector. Notably, in 2017, the world's inaugural bioenergy carbon capture and storage (BECCS) plant commenced operation at a US ethanol facility, capturing 1 $MtCO_2$ annually. By 2021, multiple ethanol plants were capturing carbon, totaling 2.21 $MtCO_2$ annually. Roughly half of this capacity focused on CO_2 storage or use, with 1.65 $MtCO_2$ yearly earmarked for enhanced oil recovery or storage. Plans exist for approximately 40 ethanol facilities, including about 30 as part of the Midwest Carbon Express project in the United States, aiming to capture CO_2 before 2030, expanding biogenic CO_2 capture capacity to over 15 Mt. For more details on carbon capture see *Chapter 5*.

The maturity level of various technologies varies depending on the type of process used, in the image below the degree of maturity for the various supply chains is shown in **Fig. 4.9**.

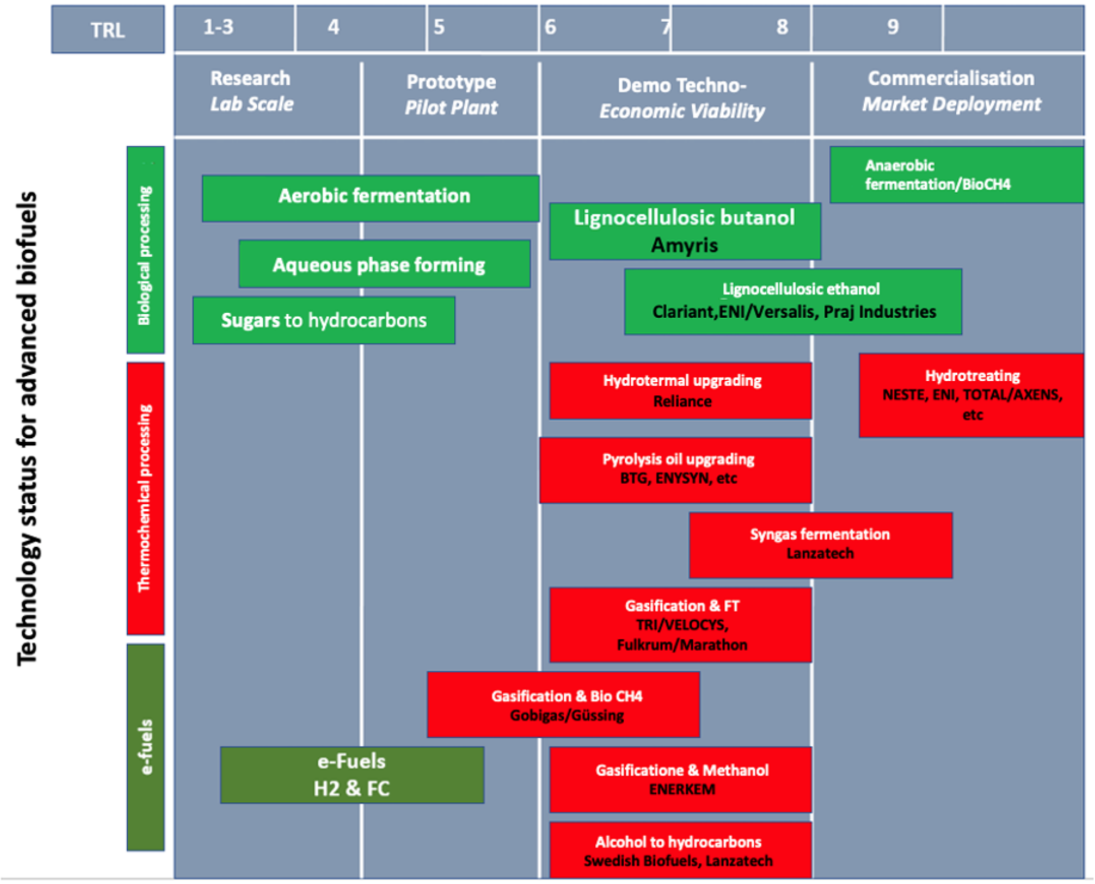


Fig. 4.9 – Status of advanced biofuels technologies based on their TRL level as well as their status based on the technology development roadmap [95].[84]

As regards industrial operators operating on advanced biofuels, these include:

- Enerkem (Canada) builds gasification plants for the conversion of solid urban waste into methanol/ethanol
- BTG-BTL technology has created systems based on fast-pyrolysis technology that consists of a thermochemical decomposition of biomass through rapid heating, at a temperature of 450 – 600 °C in the absence of oxygen.
- Clariant has recently built a plant in Romania for the production of ethanol from straw. However, the commercial plant was closed, at the end of December 2023, due to significant financial losses.
- Lanza Tech is commercializing its technology for the fermentation of gases containing CO_2/CO into ethanol. Its subsidiary, LanzaJet, using its Alcohol to Jet technology, announced, together with partner Technip Energies, plans to produce 300 million gallons per year (approximately 1.15 million cubic meters per hour) of Sustainable Aviation Fuel. LanzaJet's drop-in SAF is compatible with existing aircraft and infrastructure but has a significantly lower carbon footprint than conventional fossil fuels in terms of the life cycle. SAF produced using the LanzaJet ATJ process can reduce greenhouse gas emissions by up to 70%, depending on the ethanol source.
- ENI-Versalis in Crescentino in Piedmont is relaunching the 25,000 t/year advanced bioethanol production plant from residual biomass. ENI also produces HVO from waste oils in the biorefineries of Venice and Gela and mixes it up to 15% with fossil diesel to obtain the premium Eni Diesel+ fuel which is distributed in over 3,500 service stations across the country.

- NextChem and its subsidiary MyRechemical (Maire Tecnimont Group) are active in the development of plants for the production of renewable and recycled carbon dimethyl ether from waste and in the production of ethanol and hydrogen.

E-fuels on the other hand are synthetic fuels, produced from hydrogen produced through electrolysis powered by renewable energy and CO_2 or N_2 if the final product is ammonia. Their supply chain is less mature, but worth mentioning are:

- Germany-based Sufire specializes in the production of e-fuels using high-temperature electrolysis and CO_2 capture
- Neste, based in Finland, one of the world's leading e-fuel producers, marketing a range of renewable fuels, including renewable diesel and jet fuel

Other active players in the sector include: Ineratec, in Germany; Repsol in Spain; Carbon Recycling International (CRI) in Iceland; Climeworks in Switzerland.

4.6 Conclusions

The modern challenge of decarbonizing the transportation sector necessitates a shift from fossil fuels to renewable energy sources. The quest to reduce CO_2 emissions in transportation, constituting a significant portion of global emissions, requires a multifaceted approach. Biofuels can emerge as a key player in this transition, offering a low-carbon alternative for existing transportation technologies. However, the journey towards their diffused use faces various hurdles. These include technological barriers in producing biofuels with properties matching fossil fuels, concerns about the sustainability and sourcing of raw materials, and the need for stringent environmental governance to ensure the overall reduction in lifecycle greenhouse gas emissions.

The current market trends underscore the importance of biofuels in the roadmap to achieve Net Zero Emissions by 2050. The projected growth in biofuel demand, especially of advanced biofuels produced from feedstocks like waste and residues, highlights the potential for biofuels to help in the decarbonization of the transportation sector. Governments and international collaboration efforts play pivotal roles in fostering this transition. Regulatory frameworks, sustainability standards, and financial incentives are crucial in propelling biofuel adoption. However, the scale of required growth demands innovation and rapid deployment of advanced technologies that utilize non-food crops and waste resources efficiently.

The main challenges for the market adoption of advanced biofuels remain the lack of cost competitiveness compared to existing conventional biofuels derived from food crops and fossil fuels (estimated to be 1.5 to 3 times the market price), high capital expenses, and the availability of sustainable feedstock for biomass. There is a significant potential for cost reduction of 25-40% through research and innovation and a further 50% reduction through large-scale implementation and co-processing in existing facilities. Schemes like Emissions Trading System could also help narrow the price gap with fossil fuels: for example, the EU ETS attributes an emission factor of zero to emissions resulting from the combustion of sustainable biofuels compliant with sustainability criteria established by the RED directives.

The economic landscape surrounding biofuel remains nevertheless influenced by fluctuating prices and geopolitical events, highlighting the need for a robust and adaptable implementation strategy. Moreover, sustainability frameworks and policies should consider both environmental objectives and potential impacts on food security, striking a balance between immediate challenges and long-term sustainability goals.

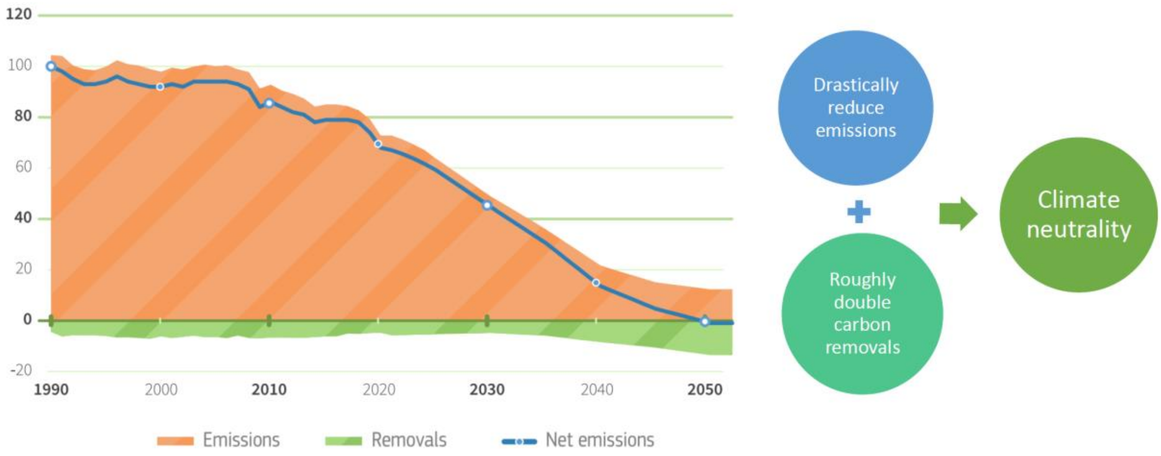
Chapter 5

Carbon capture and utilization

While crucial, renewable advancements might not counter carbon emissions at the needed pace. Hence, Carbon Capture Utilization and Storage (CCUS) is discussed as a pivotal climate mitigation strategy, highlighting its potential in offsetting emissions, particularly in "hard to abate" sectors.
CCUS encompasses diverse technologies, notably BECCS and DACS, showing promise but with distinct characteristics. BECCS, is more cost-effective due to higher pre-capture CO_2 *concentrations, while DACS, offers location flexibility but demands significant energy resources.*
Nature-based solutions, like reforestation and afforestation, although pivotal, are characterized by substantial land requirements.
Finally, Biochar's potential for carbon sequestration is highlighted, emphasizing its ability to remove significant CO_2 *quantities from the atmosphere for long-term periods. A combination of these strategies offers a powerful toolbox to achieve net zero emissions.*

5.1 Introduction

The Paris Agreement sets the ambitious goal of limiting the increase in the average global temperature to 2°C, actively pursuing efforts to limit it to 1.5°C (see *Section 3.3*). However, achieving this goal solely through the use of renewable technologies might be unattainable. Indeed, the pace of renewable technology development cannot match the rate at which the world emits carbon dioxide. Therefore, to eliminate existing emissions and halt ongoing carbon emissions, carbon capture and removal must significantly increase. Scientists have estimated that the world will need to remove up to 10 $GtCO_2$ annually from the atmosphere by 2050 to decarbonize. This removal capacity should double each year by 2100, as shown in **Fig. 5.1**.



GHG projections for climate neutrality
1990 GHG emissions = 100
Source: EU 2030 Climate Target Plan

Fig. 5.1 – GHG projections for climate neutrality (1990 GHG emissions = 100). Source: EU 2030 Climate Target Plan.

Carbon Capture Utilization and Storage (CCUS) holds significant strategic value as a climate mitigation option, applicable across various technologies and processes, and the IEA estimated that in total it will contribute to 15% of the cumulative CO_2 reduction [96]. A notable first use-case is the capture of CO_2 produced by existing fossil fuel-powered power plants, which represented approximately 60% of global emissions in 2019. Several countries are decommissioning such plants: Germany has for example plans to decommission about 40 GW by 2038, with a €40 billion package compensating coal mine and power plant owners [97]. However, most plants are located in China, and it is estimated that around 40% will likely remain operational by 2050.
Achieving zero-emission goals requires addressing emissions across all energy sectors, including those often labelled as "hard to abate". This encompasses heavy industries like cement production, steel manufacturing, and the chemical industry. The effectiveness of capturing, transporting, utilizing, or storing CO_2 as a mitigation strategy depends on technology availability at every process stage and the development and expansion of CO_2 transport and storage networks.

CCUS technologies currently vary in maturity levels, with some already implemented on a large scale while others require further development. The technology readiness level applied by the IEA to a selection of technologies along the CO2 value chain is shown in **Fig. 5.2**. Delving into the specifics of various technologies and applications isn't within the scope of this work, but an overview of the most relevant technologies for this work is presented in the following sections.

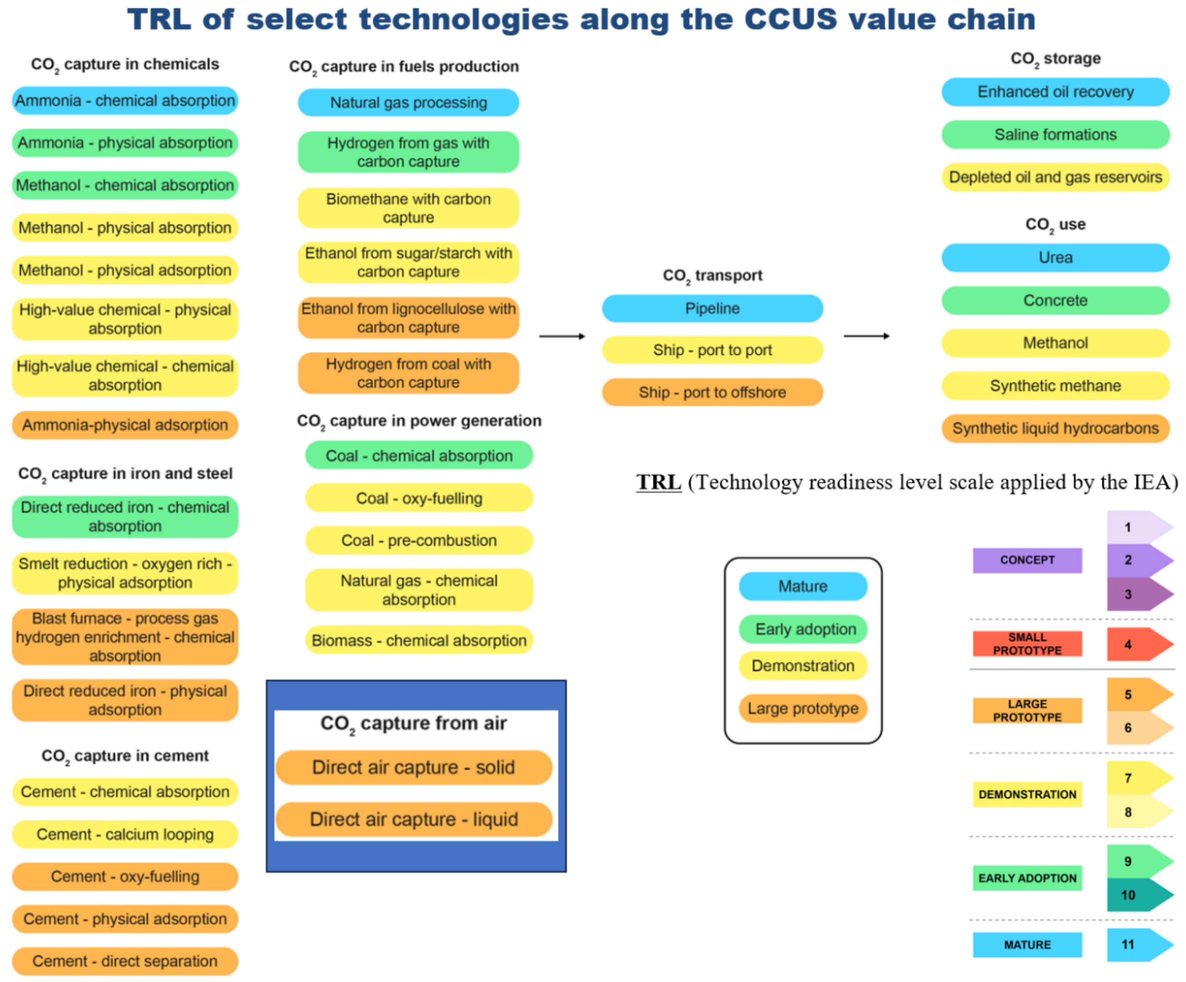


Fig. 5.2 – TRL of select technologies along the CO2 value chain [96].

The European Commission outlines four criteria under the acronym *QUALITY* for carbon absorption activities:

- Quantification: Accurate measurement of carbon absorption activities, producing unequivocal climate benefits. The additional absorptions generated should exceed the greenhouse gas emissions caused throughout the entire lifecycle of the activity. The net carbon absorption benefit should be validly and accurately quantified.
- Additionality: The absorptions should surpass the thresholds set by law.
- Long-term storage: The absorbed carbon should be stored for as long as possible, minimizing the risk of release. Certificates will indicate the storage duration, distinguishing between permanent and temporary storage.
- Sustainability: Absorptions should contribute to sustainability objectives such as climate change adaptation, circular economy, protection of water and marine resources, and biodiversity.

5.2 CCSU approaches and technologies

Methods for carbon removal involve the extraction of CO_2 from the atmosphere, either directly or indirectly (e.g., CO_2 absorption in biomass) followed by its transportation and use or permanent storage (**Fig. 5.3**). The primary appeal of these technologies lies in their ability to compensate for remaining emissions from the infamous "hard to abate" sectors, aiding the achievement of net-zero emissions. A part of the removed CO_2 could be used in products like concrete. However, a more extensive carbon removal will likely necessitate geological storage. CCUS should not be considered an alternative to immediate emission reduction actions or a cause for delaying current measures, but rather regarded as part of a comprehensive toolkit to cut emissions both presently and in the future. Additionally, supporting these technologies can act as a precaution against potential delays or shortcomings in the development and deployment of other CO_2 reduction technologies.

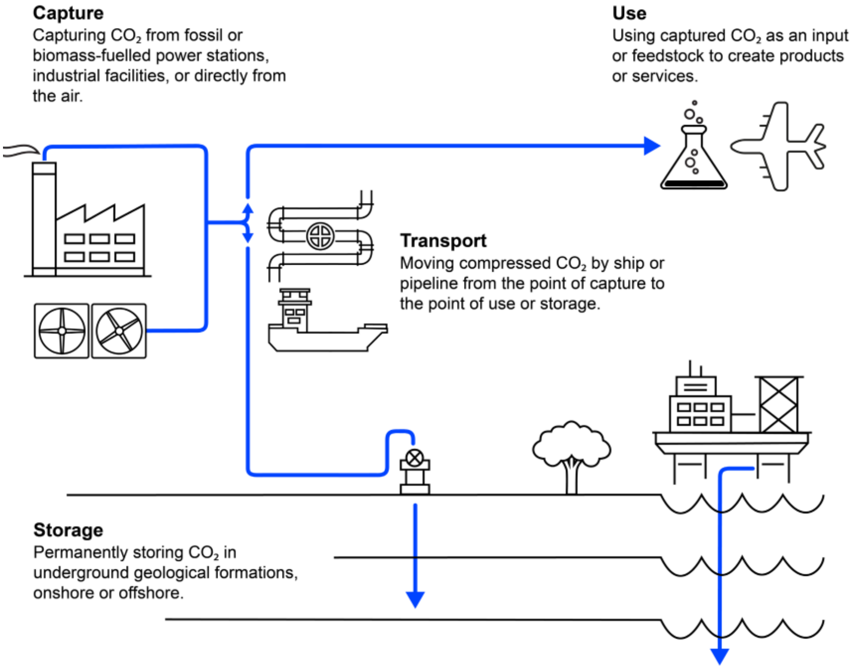


Fig. 5.3 – CCUS schematic diagram [98].

Approaches to carbon removal include natural methods, enhanced natural processes, and technological solutions (**Table 5.1**). Nature-based solutions involve strategies like afforestation (establishing forests in new areas) and reforestation (re-establishing former forested areas). Enhanced natural processes refer to land management techniques enhancing soil carbon content through modern farming practices (e.g., using biochar or fine mineral silicate rocks) and ocean fertilization, aiming to increase CO_2 absorption in oceans. On the other hand, BECCS and DACS stand out currently as primary technological solutions within the energy sector's pursuit of carbon removal towards achieving net-zero emissions.

Table 5.1 – Potential, breakeven cost, storage time, and likelihood of release for selected NETs [61].

Technique	**Removal ($GtCO_2$/yr)**	**Cost (USD/tCO2)**	**Storage duration**	**Permanence**
Forestry techniques	0.5-3.6	-40 to 10	Standing forests and long-lived wood products (decades to centuries)	Low
Land management	2.3-5.3	-90 to -20	Soil organic carbon (years to decades)	Low
Biochar	0.3-2.0	-70 to -60	Black carbon (decades to centuries)	Medium
BECCS	0.5-5.0	60-160	Geological sequestration (millennia)	High
Enhanced Weathering	2.0-4.0	<200	Aqueous carbonate (centuries)	High
DACCS	0.5-5.0	200-600	Geological sequestration (millennia)	High

While these methods can complement each other, technological solutions have some important distinguishing factors compared to nature-based alternatives. They offer verifiable and permanent underground storage, are less susceptible to weather events (like fires releasing stored CO_2 from biomass) and demand much less land area. BECCS and DACS are further along in deployment compared to some carbon removal methods. Land management and afforestation/reforestation are in early adoption stages and are constrained by land demands for food production. Non-technological methods such as enhanced weathering (dissolving minerals to remove CO_2) and ocean fertilization/alkalinization (adding alkaline substances to enhance oceans' carbon absorption capability) are in early research stages, making their potential, costs, and environmental impacts still uncertain.

BECCS, DAC, land management approaches (using biochar for example), and ocean fertilization/alkalinization hold substantial cumulative potential [98], but carry potential negative effects like land use changes, impacts on food security and biodiversity (BECCS, land management), high CO_2 capture costs (DAC), and ocean eutrophication (ocean fertilization/alkalinization). DAC requires the smallest land footprint among the more mature carbon removal options, while BECCS and afforestation/reforestation vary in land needs, primarily dependent on biomass sources.

Bioenergy with carbon capture and storage (BECCS)

BECCS involves capturing and permanently storing CO_2 resulting from processes where biomass is converted into energy or used to produce materials [98]. Biomass power plants, paper mills, cement production kilns, and biofuel production facilities are notable examples. Waste-to-energy plants can also generate negative emissions if powered by biogenic fuel. BECCS stands as the most mature among all carbon removal technologies, with both bioenergy production and CCS separately proven at commercial scales. It is applied across fuel processing and energy generation sectors, exhibiting varying maturity levels depending on the specific application. Advanced BECCS projects capture CO_2 from ethanol production or biomass-based energy generation, while industrial BECCS applications are currently in the prototype stage [98].

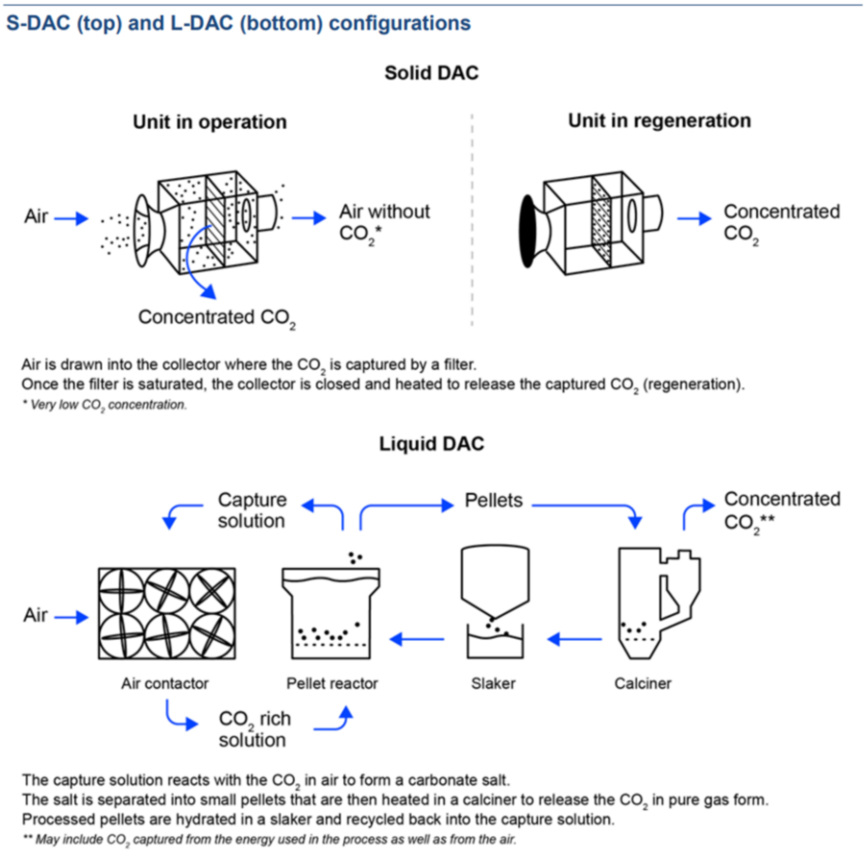
Direct air capture (DAC)

Direct air capture technologies extract CO_2 directly from the atmosphere for permanent storage (DACS) or utilization, such as in food processing or the production of synthetic fuels. Presently, these technologies rely on solid sorbents (Solid DAC or S-DAC) or liquid sorbents (Liquid DAC or L-DAC).

S-DAC relies on solid adsorbents operating through a cyclic process (**Fig. 5.4**) of adsorption/desorption. Adsorption occurs at ambient temperature and pressure, while desorption happens at low pressure and medium temperature in a cyclical process, also generating secondary production of water.
A single unit of solid adsorption/desorption has a capture capacity of several tens of tons of CO_2 per year (approximately 50 tCO_2/year) and can be used to extract water from the atmosphere (around 1 ton of water per ton of CO_2 [99]).

L-DAC relies on two separate closed chemical loops (**Fig. 5.4**). In the first loop, atmospheric air comes into contact with a basic aqueous solution (like potassium hydroxide), capturing CO_2. In the second loop, the captured CO_2 from the solution is released in high-temperature units (between 300°C and 900°C). Besides thermal energy, liquid sorbent plants, L-DAC, also require a water quantity dependent on local meteorological conditions. Under environmental conditions of 64% relative humidity and 20°C, about 4.7 tons of water are needed per ton of captured CO_2 [99].
The advantage of DAC with respect to other technologies lies in its potential flexibility of location. For instance, a DAC plant could be positioned next to a facility needing CO_2 as a raw material or above a geological storage site to reduce the need for CO_2 transport. DAC structures can also be co-located with

other CO_2 capture facilities, such as electric or industrial plants equipped with CCUS, to access existing CO_2 transport infrastructures, enabling these structures to achieve net-zero or even negative emissions.



Air is drawn into the collector where the CO_2 is captured by a filter.
Once the filter is saturated, the collector is closed and heated to release the captured CO_2 (regeneration).
* *Very low CO_2 concentration.*

The capture solution reacts with the CO_2 in air to form a carbonate salt.
The salt is separated into small pellets that are then heated in a calciner to release the CO_2 in pure gas form.
Processed pellets are hydrated in a slaker and recycled back into the capture solution.
** *May include CO_2 captured from the energy used in the process as well as from the air.*

Fig. 5.4 – S-DAC and L-DAC configurations [99].

The main disadvantage of DAC is the low concentration of CO_2 in ambient air compared to other CO_2 sources like power plants or industries, making this technology energy-intensive and expensive compared to other carbon removal options. The amount of thermal and electrical energy varies depending on the type of technology and the need to compress CO_2 for transport and storage (**Fig. 5.5**). Technologies using liquid sorbents (L-DAC) require relatively small amounts of electricity (less than 5% of the total energy requirement), while technologies using solid sorbents require more (23%).

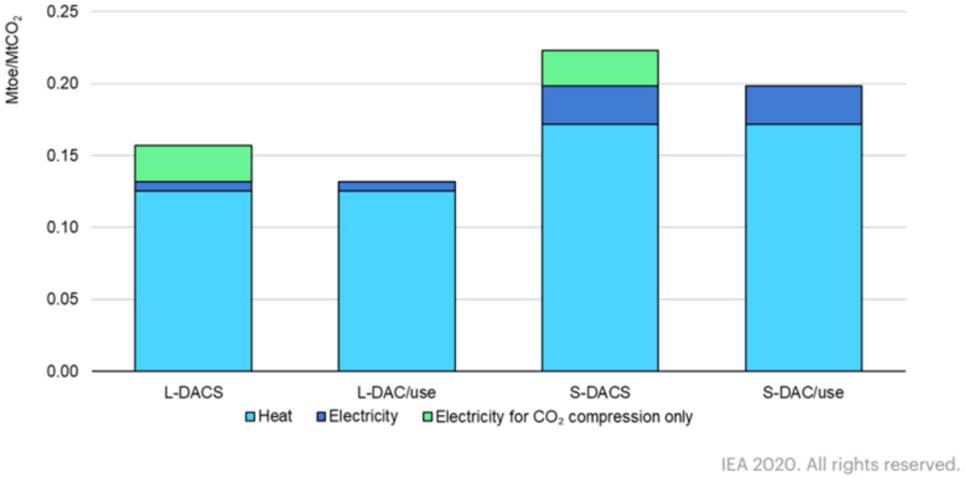


Fig. 5.5 – Specific energy consumption for CO_2 capture using current DAC technologies [98]. Actual energy needs depend on the technology and whether the CO_2 is compressed for storage or used at low pressure.

Several companies have developed technologies for direct air capture, such as:

- *Carbon Engineering* is a Canadian company founded in 2009 by David Keith, a professor at Harvard University [100]. The company's approach relies on using absorption technology with an aqueous solvent. Carbon Engineering constructed its first pilot plant in British Columbia (Canada) in 2015 and have been working on a commercial plant in the Permian Basin (TX, USA) with a capture capacity of 1 MtonCO_2/year.

- *Climeworks* is a Swiss company spun off from ETH Zurich, founded by engineers Christoph Gebald and Jan Wurzbacher in 2009 [101]. The company developed its first prototype in 2013. Currently, they have a commercial plant located in Hinwil (Switzerland), with a capture capacity of 900 tons of CO_2 per year and in Hellisheidi (Iceland), named Orca, capable of capturing and storing CO_2 700 meters underground, with a capacity of 4000 tons of CO_2 per year, which is mixed with water and pumped underground, where, through mineral carbonation, it reacts with basalt rocks. For mineralization, Climeworks collaborates with the Icelandic company *Carbfix*, specialized in rapid underground mineralization of CO_2. Renewable geothermal energy is utilized for the adsorbent bed regeneration phase with a geothermal power plant. Overall, Climeworks has 14 pilot plants in Europe (with a net removal capacity of 2000 tons of CO_2 per year), utilizing renewable energy as the energy source and reusing captured carbon dioxide for fuel, food, and beverages production. This company aims to remove 225 million tons of CO_2 (approximately 1% of total global emissions) by 2025 [102]. Climeworks also has a pilot plant in Italy, in Troia (Foggia), developed within an EU project (Store&Go), where captured CO_2 (potential of 150 tons/year) is used to produce methane [103].

- Global Thermostat was founded by Peter Eisenberger, a professor at Columbia University, in 2010 in New York (USA). This company has a pilot plant at the Stanford Research Institute (SRI) International in Menlo Park (California), based on the adsorption process [101]. Similar to Climeworks, the plant is modular, with a capacity of 1,000 tons of CO_2 per year. Global Thermostat has other pilot plants in Magallanes (Chile) and in Oklahoma (USA), where captured carbon dioxide is used for fuel production. In the future, the company aims to expand its technology into a structure capable of capturing 1 million tons of CO_2 per year [102].

- Hydrocell is a Finnish company founded in 1993 [104]. The process used involves a standard transport container, completely portable, capable of capturing 1,387 tons of CO_2 per year.

- Skytree, founded in 2008 in Amsterdam as a spin-off from the European Space Agency [105]. Small modules are used, and the captured CO_2 is used to enhance algae.

- Infinitree, founded in 2014 in New York [106], uses a capture process based on oscillating humidity adsorption using an ion exchange absorbent, with a capture capacity of 100 tons of CO_2 per year.

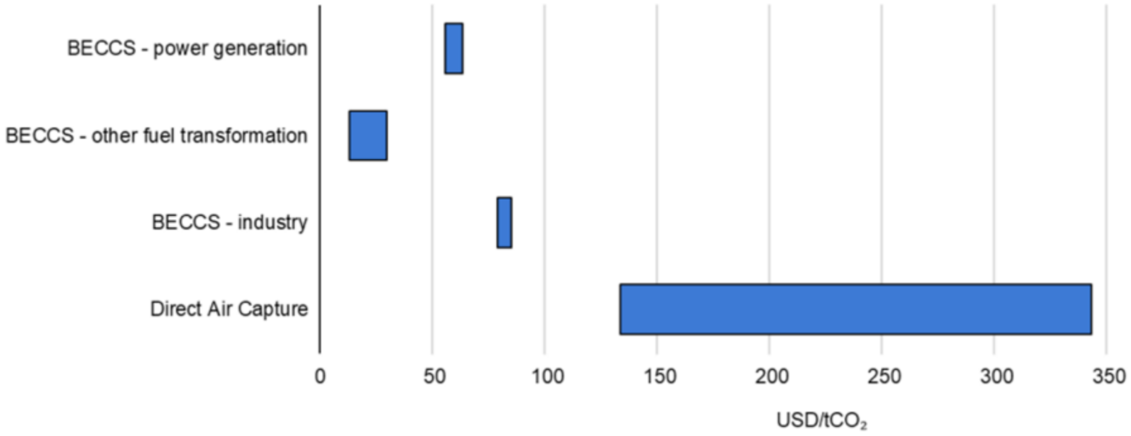
- Aker Carbon Capture stands as one of the largest and most well-established companies in the carbon capture sector. It's among the few publicly listed companies using its own solution to capture CO_2 from exhaust gases across various sectors like oil refineries and cement plants. Its key offerings include easily transportable and installable modular solutions. They also provide offshore and integrated solutions. One of their recent key projects is the Brevik cement plant [107], with a CO_2 capture capacity of 400,000 tons per year.

- Carbon Clean (London), employing its proprietary technology for CO_2 capture, established an industrial-scale plant in Chennai, India, with an annual capacity to capture 60,000 tons. In 2021, the company launched its new solution, CycloneCC, capable of achieving carbon capture rates exceeding 90%. The company prides itself on being economically advantageous, claiming to capture CO2 for less than $30 per ton.

A comprehensive overview of the currently operational DAC facilities worldwide is provided by the International Energy Agency [99]. Ozkan et al. report that globally, the operational facilities capture 10,000 tons of CO2 annually [108]. However, to meet the global goals outlined in international agreements, an estimated 13,000 DAC facilities with a capture capacity of 1 million tons of CO_2 per year are estimated to be necessary [109].

5.2.1 BECCS and DAC comparison

Currently, BECCS stands out as the most cost-effective among technology-based carbon removal approaches (**Fig. 5.6**). The higher initial CO_2 concentration pre-capture results in lower capture costs, explaining why BECCS is more economical than DAC. Specifically, capturing from fuel conversion processes (such as bioethanol production) or biomass gasification currently prove the most cost-efficient, ranging from approximately $15/tCO2 to $30/tCO2 [98]. Capturing from biomass-based electricity production costs about $60 per ton, while BECCS applied to industrial processes has a capture cost of around $80/t.



Notes: CO_2 capture costs are based on the following assumptions: technical lifetime = 25 years; representative discount rate = 8%; the price of fuel = USD 7.50/GJ; the price of electricity = USD 6.7/GJ. BECCS applied to industrial processes is based on chemical absorption.

Sources: EASAC (2018), Fuss et al. (2018), Haszeldine et al. (2018), Keith et al. (2018), Realmonte et al. (2019).

Fig. 5.6 – Cost of CO_2 capture for carbon removal technologies by sector [98].

DAC capture costs are significantly higher compared to BECCS, ranging from 2 to 25 times more, primarily due to the lower initial CO_2 concentration compared to industrial streams. DAC costs vary depending on the technology type (solid or liquid) and whether the captured CO_2 needs high-pressure compression for transport and storage instead of immediate use at low pressure. Since the technology is yet to be demonstrated on a large scale, future costs remain uncertain. The range of cost estimates in existing literature is quite broad, generally spanning from \$100/tCO_2 to \$1,000/tCO_2. Carbon Engineering has suggested achievable costs ranging between $94/t and $232/t, dependent on financial assumptions, energy costs, and specific plant setups [110].
Energy requirements of a DAC plant are a critical factor in determining its location and production costs. The site selection must consider the source of thermal and electrical energy, which will also eventually determine if the plant is carbon negative. For instance, low-carbon energy sources like solar thermal, photovoltaic (PV) systems, and wind power could effectively power DAC plants in remote areas.

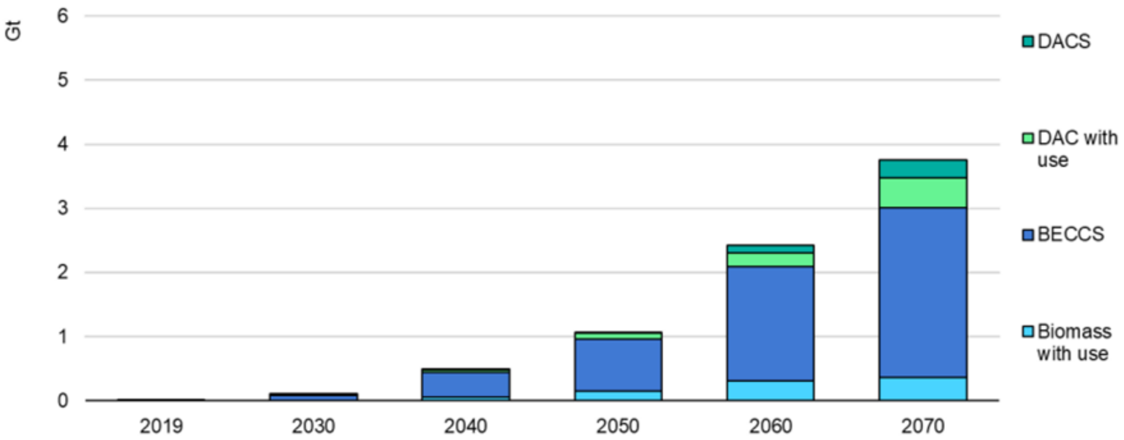


Fig. 5.7 – Global CO_2 capture from biomass and DAC according to IEA Sustainable Development Scenario [98].

The IEA net zero scenario incorporates both DACS and BECCS to achieve net zero emissions [99]. Their contribution evolves from a limited but nevertheless ambitious role in 2030 (**Fig. 5.7**), to a more substantial utilization in 2050. The captured and stored volumes reach approximately 2.7 Gt for BECCS and nearly 0.3 Gt for DACS by 2070 (**Fig. 5.7**).

Significant concerns persist regarding land area requirements associated with both BECCS and DACS. The land footprint for BECCS is estimated between 1,000 and 17,000 km^2 per Mt of removed CO_2. The land requirement for DAC is lower, maxing out at about 15 km^2 per Mt of removed CO_2, including space needed for photovoltaic solar panels if they're the sole electricity source for operating the plants. Therefore, considering the sustainable scenario projecting 740 MtCO_2 captured by 2070, DAC would require approximately 10,500 km^2 of land. Achieving the same removal level through reforestation would require between 0.5 and 11.5 million km^2, the latter being a larger area than the United States.

BECCS and DACS can play a crucial role in transitioning the global energy system to net-zero emissions. Yet, considerable uncertainty remains regarding future costs and performance, the speed at which they can be commercialized, public understanding and acceptance, limits on sustainable biomass availability, and the pace at which CO_2 transport and storage infrastructure can be developed. This underscores the need for intense research and development activity to ensure these technologies are ready for large-scale implementation within the next decade, considering the necessary lead times.

5.3 Nature-based solutions

Besides technological methods for CO_2 absorption, significant emphasis is placed on afforestation and reforestation for the future. At the European Union level, the LULUCF Regulation sets an EU-level net removal target of 310Mt CO_2e by 2030, with national targets for each Member State. In 2021, the EU's LULUCF sector accounted for the net removal of 230Mt CO_2eq, equal to 7% of the EU's total greenhouse gas emissions and it is estimated to account for 244 Mt CO_2eq in 2022. Overall, CO_2eq removals have decreased in the past 10 years, mainly as a result of increased harvest of wood as well as lower sequestration of carbon by ageing forests in some Member States. Natural disturbances (e.g. wind throws, forest fires, droughts) cause inter-annual variations, and their increasing frequency has likewise been negatively affecting long-term trends. To a lesser extent, a decreased rate of net forest area gain has also contributed to the reduction in removals.

Member State projections submitted in 2023 suggest that net removals will decrease at EU level, from an average of 314Mt CO_2eq per year in 1990-2020 to 226Mt CO_2eq in 2021-2050. Additional measures reported by Member States are expected to increase average net removals in 2021-2050 (11% compared to existing measures scenario). The projections show that for 2030 net removals of 240Mt CO_2eq are expected with existing measures and 260Mt CO_2eq with planned additional measures. This means at present, the EU is not on track to meet the 2030 net removal target of 310Mt CO_2eq. This target entered into force in May 2023 and some countries may have not begun establishing the requisite measures and reflect these in their projections. However, discounting preliminary 2022 data, the last 10-year trend has consistently pointed in the wrong direction. There is, therefore, a need to both reverse the trend as well as to accelerate in the right direction. This requires significantly more ambitious removal measures to be implemented in the coming years. Some measures with additional mitigation potential are increased afforestation, decreased deforestation, improved forest management, improved crop rotation and improved grassland management. However, for many of the measures there is a challenge with the time lag between when a mitigation measure is implemented and the results.

5.4 CO_2 capture through Biochar

Biochar is a stable carbon-based product derived through thermochemical processes from by-products, waste, or plant and/or animal biomass with applications in sustainable and conservative agriculture as well as industrial settings. It is currently used to improve the physical, chemical, and/or biological properties of soil, and beyond that, it finds applications in construction (such as insulation material) or as a system for environmental filtration and decontamination, among other uses. The key difference of biochar with respect to plant biomass, lies in the rapid decomposition of the latter compared to the significantly greater stability of biochar. Consequently, considering a specific amount of carbon circulating annually through plants, half of it can be diverted from its natural cycle and sequestered in a much slower biochar cycle (refer to the accompanying graph). Biochar sequestration directly extracts organic carbon from the photosynthesis and decomposition cycle, effectively removing carbon dioxide from the atmosphere. Transforming biomass into biochar shields a significant portion of carbon from microbial breakdown. Throughout the biochar production process, roughly half of the original carbon content within the biomass is preserved in the final biochar product [111], as also shown in **Fig. 5.8**.

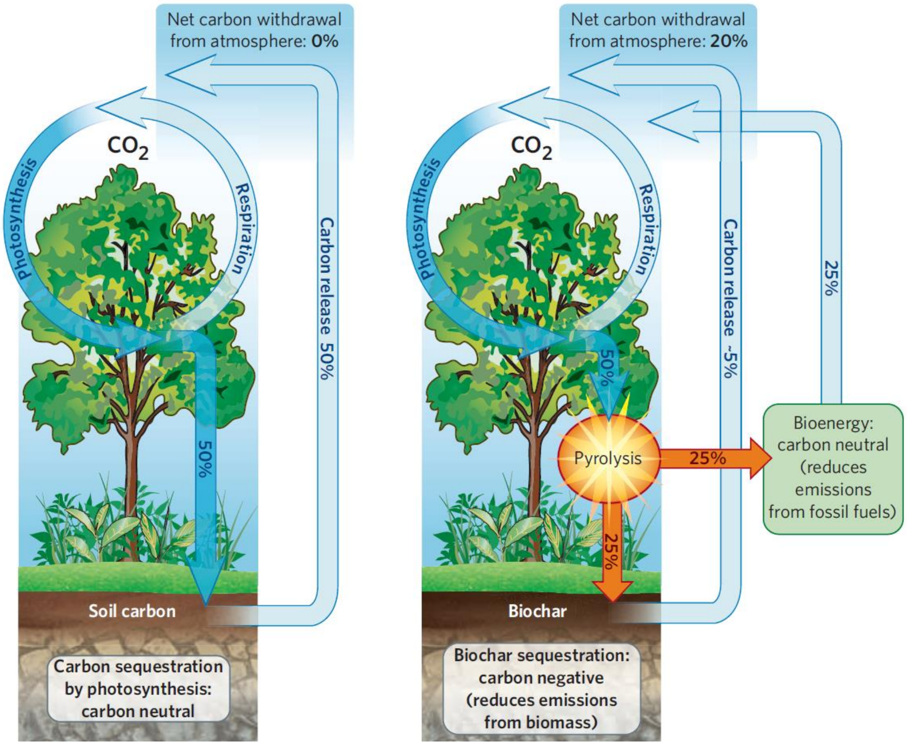


Fig. 5.8 – Decomposition of biomass with natural cycle and capture through biochar [112].

This process also triggers a reversal in the carbon cycle, as it extracts organic compounds from the active carbon pool and converts them into durable organic components [113]. While incorporating biochar into soil is estimated to result in the sequestration of approximately 50% of the initial carbon content of the biomass, in minimal amounts are retained through burning (3%) or biological decomposition (less than 10% to 20% after 5 to 10 years [114]). Emissions savings are also achieved when carbon-rich residues are converted into biochar rather than opting for compost or manure, which would otherwise be accumulated, leading to heightened methane (CH_4) emissions.

Biochar can also be combined with manure or fertilizers and adopted in no-till farming methods without the need for additional equipment. Scientific evidence has shown that biochar enhances soil structure and fertility [115], leading to improved biomass production. Beyond enhancing fertilizer retention and efficiency, biochar, through the same mechanism, can also mitigate fertilizer runoff.

Some authors have also proposed the geological sequestration of biochar in former coal mines where it could also be recovered if needed, avoiding considerations concerning the complex long-term dynamics of biochar incorporation in agrosystems [116].

Biochar is gaining interest also because its production methods are well-known and scalable from batch systems suitable for small farms or communities to large-scale industrial processes capable of converting hundreds of tons per day.

Various methods are employed in biochar production (**Table 5.2**). The most commonly used process is pyrolysis, performed in the absence of oxygen within a temperature range of 200 to 1000 °C. It is classified into slow, flash, and fast pyrolysis based on the biomass retention time in the pyrolysis reactor. The highest solid product yield (35%) is obtained through slow pyrolysis, which is therefore considered the primary method of biochar production among the three pyrolysis techniques. Flash pyrolysis, as well as gasification, have extremely low biochar yields and are typically used for gas compounds production.

Table 5.2 – Biochar preparation methods overview.

Preparation method	**Temperature (°C)**	**Heating rate**	**Reaction time**	**Yield (%)**		
				Solid	**Liquid**	**Gas**
Slow pyrolysis	<700	Slow	Hours	35	30	35
Fast pyrolysis	<1000	Fast	Seconds	10	70	20
Flash pyrolysis	775-1025	Faster	Seconds	10-15	70-80	5-20
Hydro-carbonization	<350	Slow	Minutes-hours	50-80	-	-
Gasification	700-1500	Faster	Seconds-minutes	10	5	85

Biochar contains between 80 and 90% carbon. Therefore, every ton of biochar represents an atmospheric carbon dioxide (CO_2) quantity equivalent to about three times its weight [117]. When we introduce a ton of biochar into the soil, it removes 3 tons of CO_2 from the atmosphere. Considering that biochar, once added to the soil, remains almost entirely unchanged for hundreds or even thousands of years, it serves as an excellent method for CO_2 sequestration. Through a techno-economic-environmental study of a large-scale olive tree pruning residue pyrolysis system, Fawzy et al. [118] estimated for example that after accounting for the carbon footprint of the entire process, approximately 2.68 t/CO_2eq are permanently removed from the atmosphere per ton of biochar produced. Stable carbon content was calculated as

$$Stable\ carbon\ content\ \left(\%_{dry\ basis}\right) = C_{org\ \%\ dry\ basis} \cdot F_p^{TH,Ts} \tag{5.1}$$

Where $C_{org\ \%\ dry\ basis}$ is the organic carbon content on a dry basis and $F_p^{TH,Ts}$ is the permanence factor of biochar organic carbon over a given time horizon TH and a specified soil temperature Ts. The performance factor was calculated using the formula proposed by Puro. Earth [118], according to which the performance factor is a function of the molar ratio H/C_{org}:

$$F_p^{TH,Ts} = c + m \cdot H/C_{org} \tag{5.2}$$

Numerous other studies have explored the potential of biochar in emissions reduction, which depends on the availability of biomass and environmental conditions at the site. Lefebvre et al. [119] conducted a study to assess its global potential. The availability of raw material for conversion into biochar was determined using data from the Food and Agriculture Organization website, and the quantification of biomass residues was based on a residue/product ratio. The long-term stability of carbon sequestrated in biochar was estimated using a performance factor (i.e., the fraction of carbon in biochar that is expected to remain stable in the soil over time, contributing to the long-term sequestration of carbon dioxide) which was correlated to soil temperatures based on data from Woolf et al. [120].
National average soil temperatures were obtained using QGIS software, converted to soil temperature using the equations proposed by Jian et al. [121] and averaged per country to provide a national annual average soil temperature. Additionally, it is assumed that 30% of the total available residue is retained in the field to maintain soil health, while all residues generated in food crop processing are available for conversion into biochar. The study also considered the GHG emissions associated with the production, transport, and application of biochar, including the building materials necessary for the pyrolysis plant construction and the energy required for various processes.

The study results, shown in **Fig. 5.9**, highlight countries with the highest absolute carbon potential from biochar, in millions of tons (Mt) CO2e per year. As expected, countries with large populations, territorial areas, and agricultural production dominate the list, with the potential carbon removal from biochar for China, the United States, Brazil, and India being 468, 398, 303, and 225 Mt CO_2eq per year, respectively. The remaining countries, from Argentina to Turkey, all have biochar potential ranging from 25 to 100 Mt CO_2eq/year.

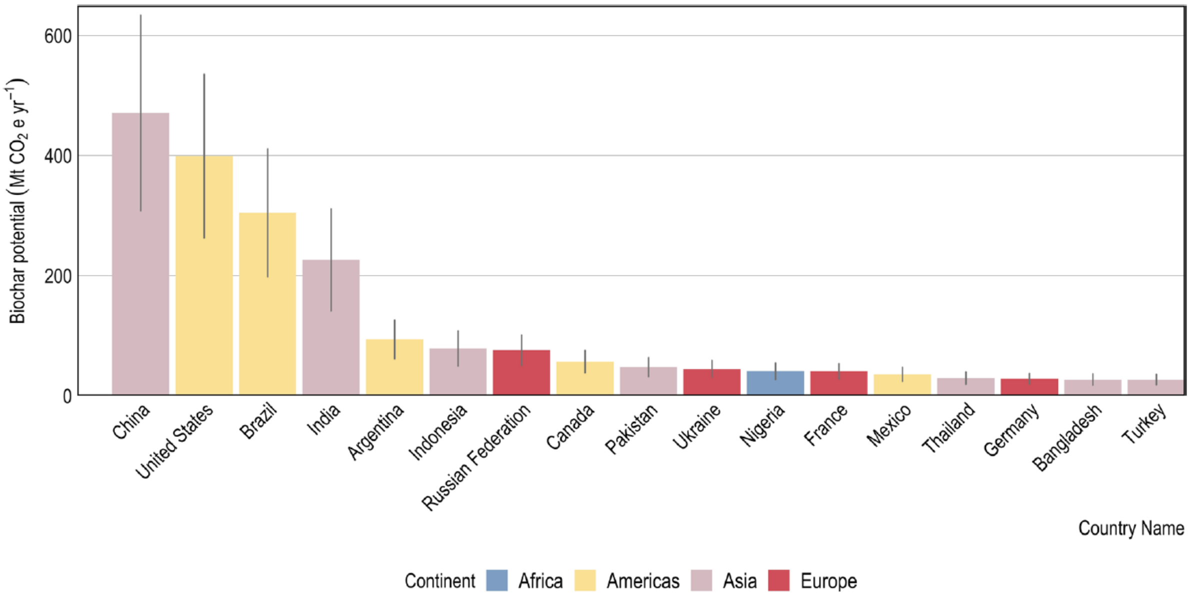


Fig. 5.9 – Countries with the largest biochar carbon dioxide removal potential. Presented data are for the 17 countries with biochar carbon dioxide removal potential > 25 Mt CO_2eq/year.[119].

Fig. 5.10 provides a global view of the potential carbon dioxide removal by biochar. A significant percentage of North and South America consists of countries with a substantial biochar potential exceeding 25 Mt CO_2eq per year. In contrast, regions with relatively low biochar potential extend from North Africa to the Middle East and are also present in smaller regions of Europe and Southern Africa. Italy falls within the range of 10-25 Mt CO2e per year.

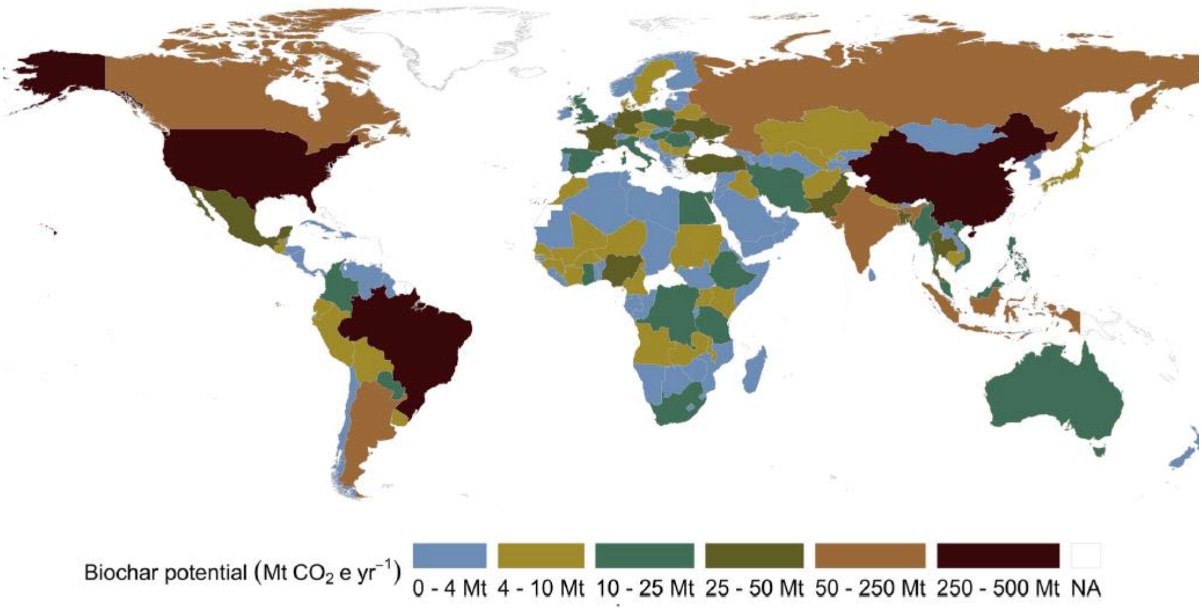


Fig. 5.10 – Global biochar carbon dioxide removal potential map (Mt CO_2eq/year) [119].

Fig. 5.11 depicts the carbon dioxide removal potential of biochar as a percentage of total national emissions in 2020, as reported by Jones et al. [122], for 28 countries where biochar has the potential to offset more than 10% of emissions. Eswatini (formerly Swaziland) stands out with the highest impact, accounting for 32% of national emissions. Additionally, three other countries exhibit impacts exceeding 20% of national emissions: Malawi (27%), Argentina (24%), and Ghana (22%).

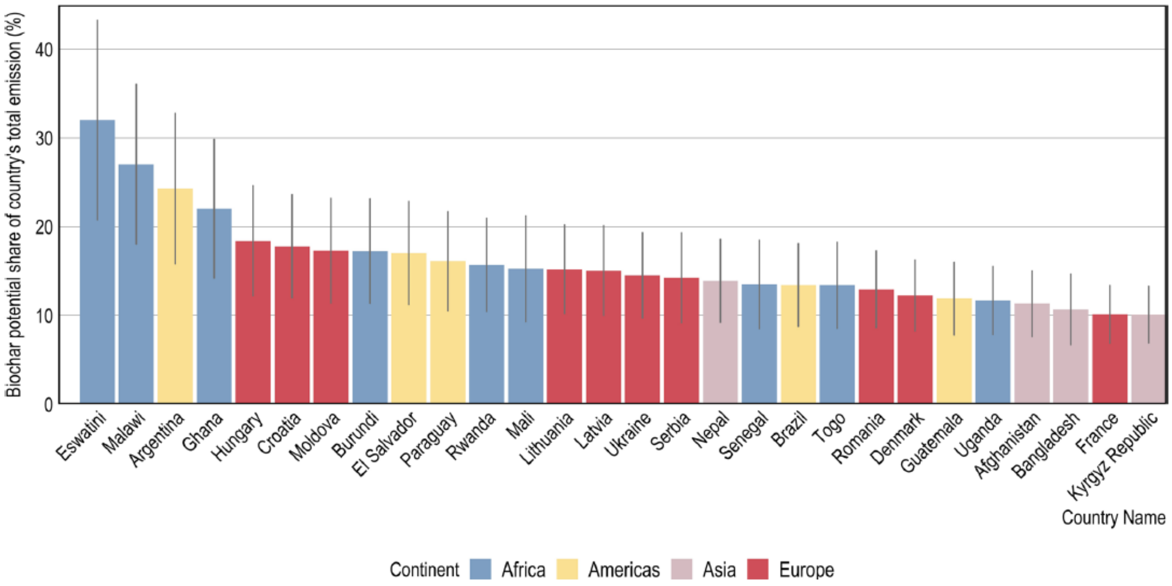


Fig. 5.11 – Countries with the largest biochar carbon dioxide removal potential as percentage of total GHG emissions [119].

Comparing **Fig. 5.11** and **Fig. 5.12**, it is evident that for five countries among those with the highest absolute potential for carbon dioxide removal through biochar the removal potential also exceeds 20% of total emissions. On global scale, these results indicate that biochar can significantly contribute to global Carbon Dioxide Removal initiatives, potentially offsetting around 6.23 ± 0.24% of total GHG emissions across the 155 countries considered by Lefebvre et al. [119].

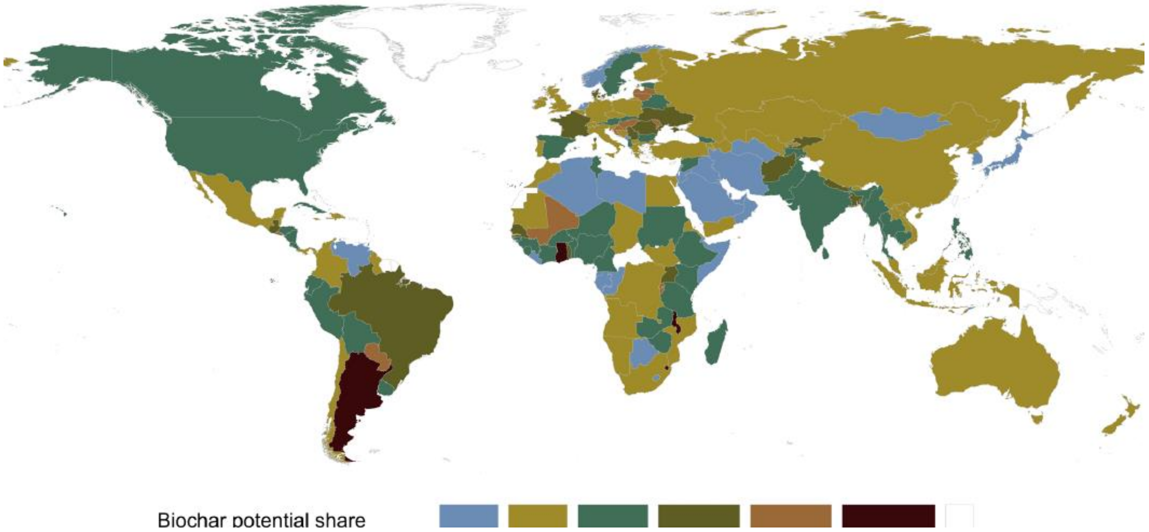


Fig. 5.12 – Global biochar carbon dioxide removal potential map as a percentage of total national GHG emissions [119].

Others study have tried to estimate the agricultural residues available at the European level with potential to be used for biochar production. Scarlat et al. [123] studied the potential residues from major crops cultivated in Europe like wheat, rye, barley, oats, maize, rice, rapeseed, and sunflower, providing detailed spatial distribution maps of different crop residue potentials at 1 km resolution. The average theoretical potential in the EU was estimated at 291 million tons dry matter (Mt DM), while at 367 Mt DM in Europe. The average technical potential of crop residue was estimated at 168 million tons dry matter per year in the EU and 212 million tons dry matter per year in Europe. Finally, the average sustainable potential, considering both technical and environmental constraints, was estimated at about 124 million tons dry matter per year in the EU and 14 Mt DM in Europe.

In addition to these, there are potential residues derived from pruning of tree crops. Indeed, according to Pari et al. [124],in Italy alone there are potentially about 6 million tons of dry matter per year from pruning residues.

According to Thengane et al. [125], the yield with which these residues can be converted into biochar varies between 15% and 35%, and this value plays an important role in the definition of the final production breakeven point. Indeed, the authors performed a technoeconomic and emissions analysis for mobile in-woods biochar production systems employing oxidative torrefaction, associated with a timber harvest. Results showed breakeven total production costs for transport, processing, and application to be in the range between 567 and 573 USD/ton biochar-C (equivalent to 392–341 USD/ton biochar). However, if the emissions from natural decay of slash (if left unprocessed) are accounted as avoided emissions, the system can reach their break-even point when CO_2 emission benefits are valued at a minimum of 85.7–118.1 USD/ton CO_2.

As mentioned above, one of the primary functions of biochar is to act as a soil amendment, improving its textural characteristics by enhancing aeration, reducing compaction, and promoting water retention. According to Gao et al. [126], the average rate of biochar application is between 10 and 20 tons per hectare, which could allow an estimation of the marginal lands that could be treated with biochar.

Current Biochar production capacity

The interest in biochar production is rapidly growing worldwide. In Europe, the production capacity continues to show significant growth. In 2022, it increased by 52%, reaching 53,000 tons of biochar production. By 2023, the production capacity is expected to grow to over 90,000 tons, representing a growth rate exceeding 80%. The estimated production from these plants (**Fig. 5.13**), assuming they operate at 60% productivity in the first year of operation and 80% thereafter, is estimated at about 35,000 tons in 2022 and 50,000 tons in 2023, equivalent to 150,000 tons of CO2e.

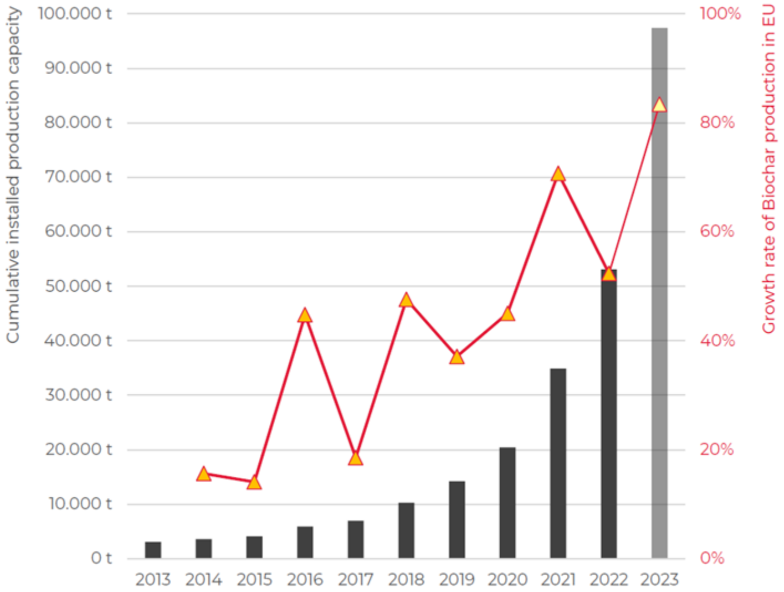
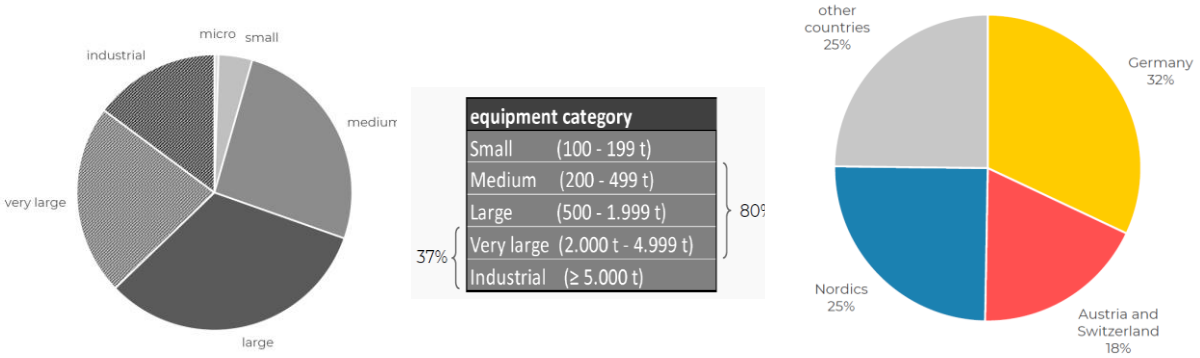


Fig. 5.13 – Cumulative installed biochar production capacity and production growth rate in Europe [117].

Regarding the size of the plants, 80% of the production capacity falls within the categories of medium, large, and very large plants, as shown in **Fig. 5.14** [117]. Meanwhile, the combined capacity of large and industrial plants accounts for 37% of the total capacity. In terms of production distribution across Europe, Germany leads with 32%, followed by the Nordic countries at 25%, and Austria and Switzerland at 18%. Italy falls within the category of other countries, and its market presence remains niche [117].
Regarding pricing in the European market, biochar is sold between 300 and 2,000 €/ton, varying based on quality, across European markets [117].



equipment category	
Small	(100 - 199 t)
Medium	(200 - 499 t)
Large	(500 - 1.999 t)
Very large	(2.000 t - 4.999 t)
Industrial	(≥ 5.000 t)

Fig. 5.14 – Biochar production in Europe by size of equipment and region/countries [117].

5.4.1 Policies, frameworks, and interaction with carbon pricing schemes

Interest in biochar for carbon sequestration and utilization within the EU is rapidly increasing. Several key policy mechanisms, including REDII, EU ETS, LULUCF, CAP, etc. are or could potentially be relevant to this topic. In the field of biofuels, the Implementing Act (IA) of RED-II and the Delegated Act (DA) on Low ILUC feedstock, presented below are particularly significant regulations pertaining to biochar, especially concerning severely degraded soils. Additionally, biochar could play a role in both compliance and voluntary carbon trading markets.
The European Union RED II acknowledges the potential of biofuel feedstock production to increase the carbon stock in agricultural soils, thus serving as a measure to mitigate greenhouse gas emissions.

Specifically, RED II incorporates a term, known as e_{sca}, in the formula for calculating the lifecycle emissions of biofuels presented in **Eq. (4.1)** which is calculate using the following formula:

$$e_{esca} = (CS_A - CS_R) \cdot 3.664 \cdot 10^6 \cdot \frac{1}{n} \cdot \frac{1}{p} - e_f \tag{5.3}$$

Where:

- CS_R is the mass of soil carbon stock per unit area associated with the reference crop management practice in Mg of C per ha;
- CS_A is the mass of soil estimated carbon stock per unit area associated with the actual crop management practices after at least 10 years of application in Mg of C per ha;
- 3.664 is the quotient obtained by dividing the molecular weight of CO_2 (44,010 g/mol) by the molecular weight of carbon (12,011 g/mol) in g CO_2eq/g C;
- n is the period (in years) of the cultivation of the crop considered;
- p is the productivity of the crop (measured as MJ biofuel or bioliquid energy per ha per year);
- e_f are emissions from the increased fertilizers or herbicide use.

This term represents the emission savings resulting from soil carbon accumulation through improved agricultural management practices. Such practices include shifting towards reduced or zero-tillage methods, implementing improved crop rotations, utilizing cover crops, managing crop residues, and employing organic soil enhancers such as compost, manure fermentation, digestate, and biochar. Each practice mentioned also corresponds to a low Indirect Land Use Change (ILUC) risk "additionality measure," which could qualify biofuel feedstock for certification with low ILUC risk.

The 'esca' term provides a mechanism for producers of crop-based biofuels to lower their reported carbon intensity, offering a means to meet progressively stricter greenhouse gas reduction requirements within the current RED framework. The maximum possible total value of the annual claim of emission savings from soil carbon accumulation due to improved agricultural management was capped in RED II to 45 g CO2eq/MJ biofuel or bioliquid for the entire period of application of the Esca practices, if biochar is used as organic soil improver alone or in combination with other eligible esca practices. In all other cases, the cap is of 25 g CO2eq/MJ biofuel or bioliquid for the period of application of the esca practices. At the international level, a comparable approach is being proposed for Sustainable Aviation Fuels, which involves integrating the carbon removal component into the formula used to calculate the greenhouse gas (GHG) performance of biofuels. Of notable significance, the REDII-IA marks the first instance of defining biochar as a sustainable agronomic practice, recognizing it as a means to enhance carbon in soil and consequently improve the GHG performance of biofuels. However, biochar is not currently listed as a sustainable practice in the LULUCF legislation. The LULUCF reporting entails assessing changes in soil carbon stocks over a specified timeframe, triggered by alterations in management practices that impact soil organic carbon under a reference condition.

Concerning the role of biochar in Emission trading systems, the EU ETS for example allows for the inclusion of biochar as a practice for reducing greenhouse gas emissions, particularly when it directly displaces fossil fuels (such as coal) in industrial processes. Hence, entities subject to the scheme can use biochar to reduce the number of allowances to surrender through improved greenhouse gas performance. Carbon removal is not included under the EU ETS, but the Commission is set to report on how negative emissions could be accounted for and covered by emissions trading.

On the other hand, Voluntary Carbon markets can exploit certified carbon removals through biochar. Biochar carbon credits are credits representing a permanent sequestration of carbon. This permanent sequestration, also called removal or drawdown, differs from avoidance or reduction credits by physically capturing carbon in a stable state for extended periods of time. Indeed, biochar typically exhibits a half-life spanning thousands of years when incorporated into soils.

The PURO Standard Biochar methodology emerged as one of the earliest approaches devised for carbon removal within the market. In 2019, it introduced the first biochar pyrolysis crediting methodology, specifically tailored to validate biochar projects and issue CO_2 removal certificates to be traded in the voluntary carbon market. This methodology establishes a framework enabling the computation of

Carbon Sequestration over 100 years (CORCs). CORCs are determined by subtracting from the carbon sequestrated over a 100-year period the lifecycle emissions from the biomass used for the production of the biochar as well as emissions arising from the production and use, including transportation of the biochar [127]:

$$CORCs = E_{stored} - E_{biomass} - E_{production} - E_{use} \tag{5.4}$$

To qualify for Puro Certification, the net balance of greenhouse gas (GHG) emissions must fall below a specific threshold, and the production process must adhere to additional conditions. These conditions include the absence of methane production during the process, ensuring sustainability in the sourcing of biomass, and an annual update of the provided data. The most recent update to the methodology occurred in 2022, expanding the scope of acceptable biomass sources and the range of technologies permissible in the biochar production process [127].
VERRA (see *Section 3.7*) has also recently released the VCS Biochar Methodology, outlining precise procedures for quantifying CO_2 emissions reduction achieved through the production and application of biochar to soil. This methodology evaluates the impact of biochar across three key phases of its supply chain: sourcing of feedstock, biochar production, and nutrient retention. It offers a standardized approach for demonstrating project additionality and establishes a monitoring and accounting framework for assessing greenhouse gas (GHG) impacts throughout these stages. The methodology is comprehensive, considering various parameters that influence both the quality of biochar and the quantity of emissions produced. Upon compliance assessment with the methodology, biochar initiatives receive VCS Certification and become eligible to receive Verified Carbon Units.

However, although biochar can find promising opportunities for widespread implementation across these markets and regulatory frameworks, particularly given the need to quickly establish nature-based sustainable removal solutions, it is imperative to emphasize the requirement for long-term studies. These studies are essential for reconciling discrepancies in emissions and determining optimal practices, of biochar application to agricultural soils [115].

5.5 Conclusions

The Paris Agreement's ambitious temperature limitation goals demand comprehensive measures beyond renewable technologies. While renewable advancements are crucial and to be given priority, they might fall short in counteracting the rapid pace of carbon dioxide emissions. Carbon Capture Utilization and Storage (CCUS) emerges thus as a crucial climate mitigation strategy, envisaged to contribute to up to 15% of cumulative CO_2 reductions. Existing fossil fuel-powered plants and "hard to abate" sectors represent notable first use-cases for this technology. However, despite recent progress, challenges remain, especially concerning technology availability and the scaling-up of CO_2 transport and storage networks.

Current CCUS technologies vary in maturity and include nature-based, enhanced natural processes, and technological solutions. While these methods can complement each other, technological solutions like BECCS and DACS have important distinguishing characteristics and will likely play important roles in emissions offsetting. BECCS stands as a mature technology, while DACS, though very promising, faces energy-intensity and cost challenges. Indeed, BECCS is currently more cost-effective due to the higher pre-capture CO_2 concentrations, while DACS, is intrinsically characterized by more flexibility in location, but demands considerable energy.
The IEA's sustainable development scenario integrates both DACS and BECCS for net-zero emissions, with a significant potential contribution by 2070. Despite their promise, the need for intense research and development activity needs to be addressed, to ensure that these technologies are ready for large-scale implementation within the next decade, considering the necessary lead times.

Nature-based solutions on the other hand have been facing challenges in meeting net removal targets, urging more ambitious measures. The EU's LULUCF regulation aims for substantial net removal but faces challenges like increased natural disturbances fires, droughts, etc.), aging forest, wood harvesting, and decreased forest area gains. Additionally, nature-based solutions are much more surface intensive the technological solutions. Considering the IEA sustainable development scenario, to achieve the needed removal level, DAC would require approximately 10'500 km^2, while reforestation would require up to 11.5 million km^2 according to some estimates.

Biochar production methods are well-established and scalable, offering versatility across various applications, including agriculture, construction, and environmental remediation. By converting biomass into biochar, a significant portion of carbon is shielded from microbial breakdown, contributing to long-term carbon sequestration.

Biochar geological storage has been proposed but its current main uses regard improving the physical, chemical, and biological properties of soil, and applications also exist in construction (such as insulation material) or as a system for environmental filtration and decontamination. It can be combined with manure or fertilizers and adopted in no-till farming methods without the need for additional equipment. Evidence has shown that biochar enhances soil structure and fertility, fertilizer retention and efficiency and that it can mitigate fertilizer runoff.

As interest in biochar production continues to grow globally, policies and frameworks are evolving to incorporate biochar into carbon pricing schemes and voluntary carbon markets. However, although biochar may encounter promising prospects for widespread implementation, further research and long-term studies are essential to address discrepancies in emissions and optimize biochar application practices.

A combination of the above strategies, pushing technological advancements while recognizing the contributions of nature-based and enhanced natural solutions like biochar, offers a multifaceted and powerful approach to address the issue of CO_2 atmospheric concentration reduction.

Chapter 6

Conclusions and perspectives

This chapter is dedicated to a summary of the main topics and points discussed. The most relevant conclusions, coming from literature review and data gathered are presented and detailed. Finally, perspectives on the evolution of carbon pricing schemes and Emission trading systems are put forward.

6.1 Conclusions

The work carried out in the present thesis analyzed possible approaches and solutions that could help in reducing global emissions and fighting climate change, one of the most difficult challenges that humanity has ever faced. A set of different strategies to achieve this goal has been analyzed, focusing in particular on innovative tools, policies, and technologies such as carbon markets, biofuels, and carbon capture technologies.

In *Chapter 1*, the status of emissions in the major industrialized and non-industrialized countries, along with their effects on climate change, have been outlined. From this, it emerges that urgent action is needed to bring emissions back under control, an endeavor in which the world will certainly be engaged in the coming years.

In *Chapter 2*, basic microeconomic tools have been applied to analyze of how the market operates with negative externalities linked to pollution. Several approaches are presented, including emission standards, Pigouvian taxes, and tradable pollution permits. The latter approach involves the issuance of emission allowances, to be allocated or sold to companies which can surrender them to cover their emissions or, if they manage to keep their emissions below the designated threshold can engage in trading excess pollution permits, thereby generating revenue from their sale. Conversely, companies that exceed their allocated quota must acquire additional permits to offset their emissions. This allows for economically advantageous emission reduction by incentivizing them where it is most costly efficient.

In the *Chapter 3*, carbon pricing and carbon markets are discussed, analyzing both compliance (carbon tax or emissions trading system) and voluntary markets. Compliance markets are tackled first starting from recalling the history of international climate agreements and discussing how they influenced environmental policy and led to regulations on emission reduction, particularly the EU-ETS. Current status of ETSs diffusion is then presented, from which it emerges that China represents the largest carbon market, covering around 2,100 plants responsible for approximately 4.5 billion tons of CO_2 emissions annually. The price of emission permits in China has however remained relatively low, averaging around \$8-10 ton/CO_2eq. The European Union constitutes the second largest ETS market by coverage but the largest in terms of traded permits. In 2022, over 15 billion emission permits were traded within the EU-ETS, with exchange values ranging between \$80-90 ton/CO_2eq, although prices have since sharp declines through 2023 and beginning of 2024.
Regarding price evolution over the years, the highest values were indeed recorded in linked EU and Swiss ETS markets, in linked markets of California and Quebec, and in New Zealand's ETS. Future trajectories in various foreign countries anticipate significant price increases, such as South Africa planning to triple its current value within a few years, or Canada aiming to reach 170 CAD (136 USD) per tCO_2eq by 2030, compared to the current price of 40-50 CAD. However, there remains much uncertainty, and the response to surging energy commodity prices, exacerbated by the current geopolitical situation, could influence these prices hikes. In fact, starting April 2022, Indonesia deferred the introduction of carbon tax due to the economic impact of soaring energy prices, while Mexico announced exemptions from carbon tax on gasoline and diesel due to market conditions.

Since its establishment in 2005, the EU-ETS (in the same way as other ETSs) has been the object of investigation concerning its role in emissions mitigation. Although the theory behind ETSs is clear, it is not as easy to evaluate empirically its effectiveness. While some studies failed to support that ETSs reduces carbon emissions, literature on the topic is abundant with sectorial studies that confirm the effectiveness of the EU ETS with some studies reporting that the EU ETS saved about 1.2 billion tons of CO_2 between 2008 and 2016 (3.8% of total EU-wide emissions) relative to a world without carbon markets, which corresponds to almost half of what EU governments promised to reduce under their Kyoto Protocol. This reduction took place despite low prices of the initial phases of the EU-ETS which could be a sign that if a carbon market is a credible institution that can plausibly become more stringent in the future, firms might cut emissions even though market prices are low. Low prices can hence be a signal that the demand for carbon permits weakens because of reduced emissions.

The work highlighted that the lack of a global carbon market and the difference in carbon prices between countries part of different emissions trading systems (ETSs) and those without carbon pricing schemes, raise concerns about the potential of ETS to cause a phenomenon referred to as "Carbon leakage", the risk of companies relocating their production to countries with less stringent policies to reduce costs. To protect the competitiveness of industries covered by the EU ETS, national governments often allocate a higher proportion of free emission allowances to sectors considered at significant risk of relocation. This can however strongly impact the effectiveness of an ETS, but at the same time consequences of emissions relocation could be far-reaching, undermining goals and credibility of domestic carbon pricing schemes and in the worst-case scenario even leading to increased global emissions. The topic was tackled by also presenting a simplified evolutionary model capable of representing economic forces at play and possibly expandable in the future to better capture interaction between different systems and introduction of new policies.

Empirical research reviewed in the chapter revealed little indications of the effective existence of carbon leakage so far. Nevertheless, carbon prices have remained very low up to very recently, and there is a high likelihood that they will rise more in the future, thus increasing the Carbon leakage risk.

The last part of *Chapter 3* revolved around Voluntary Carbon markets which operate independently of the mandatory schemes. Participants are not obligated to reduce their emissions and can choose to participate due to a sense of social responsibility, shareholder pressure, or as a strategic move. Voluntary carbon offsets are created, verified, and transacted outside of governments agencies.

Although the compliance sector currently dominates the market, voluntary carbon offsets can support a much greater range of activities in more countries. The market has shown a significant growth over the past five years, with a 252% increase since 2017 and it's estimated that the VCM attracted approximately $1.3 billion in investments during 2022, helping to offset around 161 million metric tons of greenhouse gas emissions. However, with respect to compliance markets, voluntary carbon markets have so far been characterized by lack of information and several issues which must be addressed for voluntary carbon markets to scale, including weak validation and verification processes, double counting, oversupply of poor-quality credits, regulatory uncertainty, lack of price transparency and revenue visibility with potential money laundering, unclear property rights, and so on. Therefore, it becomes crucial to define more objective quality criteria in order to avoid concerns related to the fact that voluntary offsets may offer polluting entities a simpler path to fulfill their decarbonization obligations and facilitate offsets potential integration with compliance systems. Despite these concerns, demand is expected to grow as more and more individuals and businesses start to address their carbon footprint, and according to the Taskforce on Scaling Voluntary Markets, the market is anticipated to grow approximately 15-fold, transitioning from 0.1 to 1.5-2 $GtCO_2eq$ of carbon credits annually by 2030.

The role to be played by biofuels in the future decarbonization particularly of the transport sector, as well as connections to carbon markets is addressed was addressed in *Chapter 4*. The main challenges that biofuels face is technological and environmental, concerning the nature and sourcing of raw materials. Currently, the most mature sector is that related to oils; however, the procurement of sustainable raw materials has become the primary critical element of the value chain: used oils which until recently posed a disposal problem, have reached very high prices of around €1400/ton.

The main challenges for the market adoption of advanced biofuels remain the lack of cost competitiveness compared to existing conventional biofuels derived from food crops and fossil fuels (estimated to be 1.5 to 3 times the market price), high capital expenses, and the availability of sustainable feedstock for biomass. There is a significant potential for cost reduction of 25-40% through research and innovation and a further 50% reduction through large-scale implementation and co-processing in existing facilities. Mechanisms like the Emissions Trading System could help bridge the price gap with fossil fuel since an emission factor of zero is attributed with the EU-ETS to emissions resulting from the combustion of sustainable biofuels compliant with sustainability criteria established by the RED directives. The economic sustainability and future diffusion of biofuels is influenced by fluctuating prices and geopolitical events, necessitating a robust implementation strategy. At the same time, policies should balance environmental goals with impacts on food security to achieve long-term sustainability.

Chapter 5, contains an overview of Carbon Capture Utilization and Storage technologies which emerge as a critical mitigation strategy, envisaged to contribute to up to 15% of cumulative CO_2 reductions. Various technologies have been explored, with a particular focus on direct air capture (DAC) systems and CO_2 capture within biomass energy conversion plants (BEECS), as well as carbon sequestration in biochar. Biochar can serve a dual purpose, of carbon storage and useful product which can be used both industrially and as a soil amendment to enrich the fertility of marginal lands. The analysis suggests that while DAC proves to be significantly more efficient in terms of occupied area compared to solutions like new afforestation and reforestation, but it also comes with a substantially higher cost, with a price per ton of captured CO_2 amounting to no less than €150-200. There exists substantial industrial interest in these technologies with a focus on cost reduction. As for biochar, its production attracted significant attention due to its socioeconomic implications. Various political and regulatory efforts are currently underway to integrate biochar into carbon pricing systems and voluntary carbon markets. However, although biochar may encounter promising prospects for widespread implementation, further research and long-term studies are essential to address discrepancies in emissions and optimize biochar application practices.

6.2 Perspectives

With growing international recognition of their importance, carbon markets are likely to see significant expansion. In time, a global market could emerge, but this does not seem likely in the short to medium term. Possibly more likely is the creation of economy-wide or country-wide ETS given the ongoing trend to include more and more sectors within emission trading schemes. A testimony of this is the recent inclusion of the aviation and maritime sectors in the EU ETSs and the revision of the ETS regulations starting from 2026, which should include the transport and building sectors. Although little carbon leakage has occurred so far, the European Central Bank highlighted that some has already occurred and that this phenomenon is likely to intensify as more sectors are covered, translating into a bigger competitive disadvantage for companies located into the EU (which have already been burden by the scheme) force to purchase higher cost emission regulated inputs from within the EU. The risk of fuel bunkering (maritime) and tankering (aviation) in third countries has also increased and is not helped by UK's withdrawal from the EU.

Starting from 2026 the European Carbon boarder Adjustment Mechanism (CBAM), currently in a transitional phase, should apply its definitive regime. The objective of this tool is to put a fair price on the carbon emitted during the production of goods entering the EU. By confirming that a price has been paid for the embedded carbon emissions generated in the production of certain goods imported into the EU, the CBAM will ensure the carbon price of imports is equivalent to the carbon price of domestic production, and that the EU's climate objectives are not undermined.
The CBAM corresponds to a unilateral trade measure not agreed upon at the World Trade Organization (WTO) or in other international fora such as the Paris club. It could therefore originate litigations and retaliations from other countries thus achieving the opposite result of jeopardizing exports of EU industries and impairing their competitiveness. The current proposal of the CBAM is designed to minimize the risk of originating WTO litigations, since it puts domestic and foreign production on even footing with the result that legal scholars tend to agree that the extension of the ETS to imports, as the CBAM proposes to do, complies with WTO law. In the long run, a strong form of coordination among countries, like linking their national ETSs is under consideration since it would reduce the scope for a CBAM and at the same time facilitating the convergence of methodology applied in computing emissions at national ETS.

Additionally, it is worth recalling that the EU decided in 2022 to sell €20 billion worth of permits to fund its RePowerEU program to reduce reliance on Russian gas imports. Under that program, countries

will front-load auctions that would have been sold later in the decade to fund the shift away from gas now. Because of that, the market could get much tighter in the coming years, but in the short term this added more supply in a market where emissions are dropping significantly causing a sharp price drop. Price decline and lack of clarity on how many permits the EU will sell is creating considerable uncertainty in the market with the ultimate result of sending a weaker signal for companies which might reduce the efficiency of the system in the short term to medium term.
There have been voices advocating for the establishment of an EU Carbon Central Bank, arguing that it would increase the effectiveness of carbon markets through the management of liquidity and by building confidence. Supporting arguments include the fact that the rapid pace of market movements renders automated rules like the MSR ineffective and that allowances are similar to currencies, which are traditionally managed by central banks. Such an institution could also prioritize the integration of carbon removals by sourcing removal credits and releasing them into the EU ETS market in response to demand fluctuations. This dual role could position it as both a liquidity provider and ensuring the ongoing functionality of the EU ETS and maintaining competitive industrial activity. However, there are counterarguments against the establishment of a Carbon Central Bank, suggesting that it may exert excessive influence on market dynamics, potentially shaping rather than merely responding to market forces, and thus susceptible to political interference. These considerations underscore the need for a rigorous intellectual discourse on this matter to commence promptly.

The impact of a possible recession on the EU ETS is also a complex issue with multiple mechanisms at play. Reduced demand and investment could test the Market Stability Reserve (MSR) effectiveness. Additionally, governments might be reluctant to pursue the traced emissions reduction paths and to put further strain on already struggling domestic companies or even introduce measures to stimulate the economy, potentially including relaxing environmental regulations or increasing the availability of free allowances through the (MSR), which could further suppress the allowances price.

The compliance markets continuous extension to new sectors also raises the question of the future role of Voluntary carbon markets, especially given their current lack of transparency. In the long-term Voluntary markets could differentiate themselves by offering higher-quality and verified offsets with stricter environmental and social safeguards compared to compliance markets. Voluntary markets can also address a wider scope going beyond the simple emission reductions, but uncertainty remains concerning their regulation and possible integration with or use in compliance markets.

Although the consensus is that carbon removal while play a pivotal role in achieving Net Zero, this is not included under the EU ETS. The Commission is set to report, by 2026, on how negative emissions could be accounted for and covered by emissions trading. The Innovation Fund, a key source of EU support for nascent carbon removal projects amongst other clean technologies, is funded by the auctioning of ETS allowances. At 75 euro/tCO_2, the ETS is set to provide around EUR 38 billion from 2020 to 2030 to the Fund. The discussion concerning the accounting of removals is however complex, and several challenges need to be considered including the permeance of removals and their quantification, the safety of storage and how removals can be accounted for and covered by emission trading schemes without compromising the efforts in reducing emissions which must remain the priority. The consideration of other benefits other than the simple emission reduction should also play a role in compliance markets in the future.

Finally, technological advancements and large-scale implementation can significantly reduce biofuel production costs. Integrating biofuels with carbon markets through mechanisms like the EU-ETS could further incentivize their adoption. However, ensuring sustainable feedstock sourcing remains paramount to avoid unintended environmental consequences. Biochar production is likely to see increased focus due to its potential for both carbon storage and soil improvement. Integrating biochar into carbon pricing schemes could further incentivize its adoption. With this respect connecting Negative Emission Technologies and Allowances can be very relevant for biochar.

Despite the challenges outlined, a combination and integration of these strategies offers a powerful toolbox which gives hope to achieve net zero emissions.

Chapter 7

Appendix

7.1 Carbon leakage and ETS evolutionary model Python routine

This section presents the Python routine implemented to reproduce the Carbon leakage and ETS evolutionary model proposed by Antoci et al. [64] and presented in *Section 3.6.1*.

```
import math as math
import numpy as np
import matplotlib.pyplot as plt
import sympy as sp

"Functions------------------------------------------------------------------------------------------------------ "

def Max_Pi_h(p,F,C_h_v,theta,a):
    if p<=(F*C_h_v):
        q=p/C_h_v
        z=0
        d=0
    elif p>(F*C_h_v) and p<((C_h_v*F + a)*theta + a*C_h_v)/theta:
        q=(theta*F + p)/(C_h_v+theta)
        z= (p-C_h_v*F)/(C_h_v+theta)
        d=0
    elif p>=((C_h_v*F+a)*theta + a*C_h_v)/theta:
        q= (p-a)/C_h_v
        z=a/theta
        d= ((p-a-C_h_v*F)*theta - a*C_h_v)/ (theta* C_h_v)
    else:
        print ("Max_Pi_q Error")
    return {"q":q,"z":z,"d":d}

def p_equilibrium(N,x,P_bar,alpha,Q_bar,F,C_h_v,C_h_f,theta,a,C_r_v,C_r_f):
    err = 1
    p=P_bar/N
    while abs(err)>1e-7:
        dp= p*1e-5
        # h-firms
        PI_h_opt = Max_Pi_h(p,F,C_h_v,theta,a)
        q_h_opt = PI_h_opt['q']
        z_h_opt = PI_h_opt['z']
        d_h_opt = PI_h_opt['d']
        Pi_h = p*q_h_opt - 0.5*C_h_v*(q_h_opt**2)- C_h_f- 0.5*theta*(z_h_opt**2) - a*d_h_opt
        # r-firms
        q_r_opt= p/C_r_v
        Pi_r = p*q_r_opt - 0.5*C_r_v*(q_r_opt**2)- C_r_f
        # Supply function
        S= x*N*q_r_opt + (1-x)*N*q_h_opt
        err=abs(p- (P_bar - alpha*S))

        p_1=p+dp
        q_h_opt_1 = Max_Pi_h(p_1,F,C_h_v,theta,a)['q']
        q_r_opt_1= p_1/C_r_v
        S_1= x*N*q_r_opt_1 + (1-x)*N*q_h_opt_1
        err_1=abs(p_1- (P_bar - alpha*S_1))
        deri=(err_1 - err)/dp
        p = p - err/deri
    Q_auc = Q_bar - F*(1-x)*N
    D_firms = d_h_opt*(1-x)*N
    if(q_h_opt)<0:
        print ("q_h_opt < 0")
    if (Q_bar - F*(1-x)*N)<=0:
```

```
        print("Error, maximum number of free permits that can be allocated is: ",(1-x)*N/Q_bar)


    return{"p":p,"Q_auc":Q_auc,
"D_firms":D_firms,"Pi_h":Pi_h,"Pi_r":Pi_r,"d_h_opt":d_h_opt,"q_h_opt":q_h_opt,"z_h_opt":z_h_opt}


def Market_eq(N,x,P_bar,alpha,Q_bar,F,C_h_v,C_h_f,theta,C_r_v,C_r_f,a_floor):
    a = a_floor
    a=0.15
    d_a = a + a*1e-5
    err=1
    while abs(err)>1e-6:
        Equi= p_equilibrium(N,x,P_bar,alpha,Q_bar,F,C_h_v,C_h_f,theta,a,C_r_v,C_r_f)
        err= Equi["Q_auc"]- Equi["D_firms"]
        a_1 = a + d_a
        Equi_1= p_equilibrium(N,x,P_bar,alpha,Q_bar,F,C_h_v,C_h_f,theta,a_1,C_r_v,C_r_f)
        err_1= Equi_1["Q_auc"]- Equi_1["D_firms"]
        deri=(err_1 - err)/d_a
        a = a - err/deri

    a_opt= max(a,a_floor)
    Equi= p_equilibrium(N,x,P_bar,alpha,Q_bar,F,C_h_v,C_h_f,theta,a_opt,C_r_v,C_r_f)
    p = Equi["p"]
    Q_auc=Equi["Q_auc"]
    D_firms = Equi["D_firms"]
    Pi_h = Equi["Pi_h"]
    Pi_r = Equi["Pi_r"]
    d_h_opt = Equi["d_h_opt"]
    q_h_opt = Equi["q_h_opt"]
    z_h_opt = Equi["z_h_opt"]
    return {"p":p,"Q_auc":Q_auc,
"D_firms":D_firms,"Pi_h":Pi_h,"Pi_r":Pi_r,"d_h_opt":d_h_opt,"q_h_opt":q_h_opt,"z_h_opt":z_h_opt,"a_o
pt":a_opt}


def Equilibrium (N,x,P_bar,alpha,Q_bar,F,C_h_v,C_h_f,theta,C_r_v,C_r_f,a_floor,beta):
    err=1
    while abs(err)>1e-7:
        Mkt_Equi = Market_eq(N,x,P_bar,alpha,Q_bar,F,C_h_v,C_h_f,theta,C_r_v,C_r_f,a_floor)
        Delta_Pi = Mkt_Equi["Pi_r"] - Mkt_Equi["Pi_h"]
        x1 = x/(x + (1-x)*math.exp(-beta*Delta_Pi))
        err=x-x1
        x=x1
        #x=min(0,0.9999)

    p = Mkt_Equi["p"]
    Q_auc=Mkt_Equi["Q_auc"]
    D_firms = Mkt_Equi["D_firms"]
    Pi_h = Mkt_Equi["Pi_h"]
    Pi_r = Mkt_Equi["Pi_r"]
    d_h_opt = Mkt_Equi["d_h_opt"]
    q_h_opt = Mkt_Equi["q_h_opt"]
    z_h_opt = Mkt_Equi["z_h_opt"]
    a_opt = Mkt_Equi["a_opt"]
    return {"x":x,"p":p,"Q_auc":Q_auc,
"D_firms":D_firms,"Pi_h":Pi_h,"Pi_r":Pi_r,"d_h_opt":d_h_opt,"q_h_opt":q_h_opt,"z_h_opt":z_h_opt,"a_o
pt":a_opt}
"--------------------------------------------------------------"
# Constants and Parameters
```

```
N = 50        # Total number of firms
C_h_v = 0.6  # Variable costs of h-firms
C_h_f = 0.5  # Fixed costs of h-firms
C_r_v = 0.5  # Variable costs of r-firms
C_r_f = 1.7  # Fixed costs of r-firms
Q_bar = 40
f = 0.001
F = f * Q_bar    # Free permits given to each home firm
theta = 0.17     # Abatement technology efficacy parameter
alpha = 1        # Parameter for demand function
P_bar = 150      # Equilibrium price on the output market
theta = 0.17     # Abatement technology efficacy parameter
beta = 1.5       # Imitation parameter
x = 0.013
a_floor = 0.1     # Minimum permits price (floor price)


Equi = Equilibrium(N, x, P_bar, alpha, Q_bar, F, C_h_v, C_h_f, theta, C_r_v, C_r_f, a_floor, beta)
print (Equi)

"FIG.1"

#________________________________________________
Time_vect = np.linspace(0,30,31)

x_values = []
a_opt_values = []
t_values = []
D_opt_values = []
z_opt_values = []

for t in Time_vect:
    Mkt_Equi = Market_eq(N,x,P_bar,alpha,Q_bar,F,C_h_v,C_h_f,theta,C_r_v,C_r_f,a_floor)
    Pi_h = Mkt_Equi['Pi_h']
    Pi_r = Mkt_Equi['Pi_r']
    a_opt = Mkt_Equi['a_opt']
    d_h_opt = Mkt_Equi['d_h_opt']
    z_h_opt = Mkt_Equi['z_h_opt']
    #print (Pi_h)
    #print (Pi_r)
    Delta_Pi = Pi_r - Pi_h
    x1 = x/(x + (1-x)*math.exp(-beta*Delta_Pi))
    #print(x)
    x=x1

    # Store values for plotting
    t_values.append(t)
    x_values.append(x)
    a_opt_values.append(a_opt)
    D_opt_values.append(d_h_opt)
    z_opt_values.append(z_h_opt)

# Create separate plots
plt.figure(figsize=(6, 4))
plt.plot(t_values, x_values)
plt.xlabel('Time (t)')
plt.ylabel('x')
plt.title('x vs. t')
plt.show()
```

```
# Plot 2: a_opt vs. t
plt.figure(figsize=(6, 4))
plt.plot(t_values, a_opt_values)
plt.xlabel('Time (t)')
plt.ylabel('a_opt')
plt.title('a_opt vs. t')
plt.show()

# Plot 3: D_opt and z_opt vs. t
plt.figure(figsize=(6, 4))
plt.plot(t_values, D_opt_values, label='D_opt')
plt.plot(t_values, z_opt_values, label='z_opt')
plt.xlabel('Time (t)')
plt.ylabel('Value')
plt.title('D_opt and z_opt vs. t')
plt.show()

"FIG.2"

a_floor_values = np.linspace(0.1, 0.9, 100)  # Vary a_floor from 0.1 to 0.9 in 100 intervals

x_values = []
a_opt_values = []
d_hopt_values = []
Z_hopt_values = []

for a_floor in a_floor_values:
    Equilib = Equilibrium(N, x, P_bar, alpha, Q_bar, F, C_h_v, C_h_f, theta, C_r_v, C_r_f, a_floor, beta)
    x_values.append(Equilib['x'])
    a_opt_values.append(Equilib['a_opt'])
    d_hopt_values.append(Equilib['d_h_opt'])
   Z_hopt_values.append(Equilib['z_h_opt'])

# plot 1: x vs. a_floor
plt.figure(figsize=(6, 4))
plt.plot(a_floor_values, x_values)
plt.xlabel('a_floor')
plt.ylabel('x')
plt.title('x vs. a_floor')
plt.show()
#plt.ylim(0, 0.6)

# plot 2: a_opt vs. a_floor
plt.figure(figsize=(6, 4))
plt.plot(a_floor_values, a_opt_values)
plt.xlabel('a_floor')
plt.ylabel('a_opt')
plt.title('a_opt vs. a_floor')
plt.show()

# plot 3: d_hopt vs. a_floor
plt.figure(figsize=(6, 4))
plt.plot(a_floor_values, d_hopt_values)
plt.plot(a_floor_values, Z_hopt_values, label='z_opt')
plt.xlabel('a_floor')
plt.ylabel('d_hopt')
plt.title('d_hopt vs. a_floor')
plt.show()
```

References

[1] W.P. Prospects, World Population Prospects 2022 : Summary of Results Ten key messages, (2023) 2–3.

[2] R. Gugulothu, N.S. Somanchi, H.B. Banoth, K. Banothu, A Review on Solar Powered Air Conditioning System, Procedia Earth and Planetary Science 11 (2015) 361–367. https://doi.org/https://doi.org/10.1016/j.proeps.2015.06.073.

[3] IEA, CO2 Emissions in 2022, 2023. https://doi.org/10.1787/12ad1e1a-en.

[4] J. Olivier, J. Peters, Trends in Global CO2 and Total Greenhouse Gas Emissions; 2020 Report, 2020.

[5] ISPRA, Le emissioni di gas serra in Italia: obiettivi di riduzione e scenari emissivi, n.d. https://www.isprambiente.gov.it/files2023/pubblicazioni/rapporti/rapporto_384_2023_le-emissioni-di-gas-serra-in-italia.pdf.

[6] M. Crippa, D. Guizzardi, F. Pagani, M. Banja, M. Muntean, Schaaf E., W. Becker, F. Monforti-Ferrario, R. Quadrelli, A. Risquez Martin, P. Taghavi-Moharamli, J. Köykkä, G. Grassi, S. Rossi, J. Brandao De Melo, D. Oom, A. Branco, J. San-Miguel, E. Vignati, GHG emissions from all countries, JRC, Pubblication of the European Union, Luxembourg, 2023. https://doi.org/10.2760/235266.

[7] Copernicus, Globe in 2022, 2023.

[8] Copernicus, Global temperature trend monitor, (2023). https://cds.climate.copernicus.eu/cdsapp#!/software/app-c3s-global-temperature-trend-monitor?tab=app (accessed August 28, 2023).

[9] L. Treut, R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, a Mokssit, T. Peterson, M. Prather, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, Historical Overview of Climate Change Science, Earth Chapter 1 (2007) 93–127. https://doi.org/10.1016/j.soilbio.2010.04.001.

[10] D. Besanko, R. Braeutigam, Microeconomics, 6th ed., John Wiley & Sons, Northwestern University, 2020.

[11] A. Smith, An Inquiry into the Nature and Causes of the Wealth of Nations, McMaster University Archive for the History of Economic Thought, 1776.

[12] R.K. Turner, D.W. Pearce, I. Bateman, Environmental economics: An elementary introduction, Johns Hopkins University Press, Baltimore, MD, 1993.

[13] R.K. Turner, D. Pearce, I. Bateman, Environmental economics, Johns Hopkins University Press, Baltimore, MD, 1993.

[14] A. La Gatta, Analisi del mercato dei crediti di carbonio e meccanismi di offsetting: un benchmark tra imprese del settore alimentare, Politecnico di Torino, 2022.

[15] A.C. (Arthur C. Pigou 1877-1959, The economics of welfare, Second edition. London : Macmillan, 1924., 1924.

[16] R.H. Coase, The Problem of Social Cost, J Law Econ 3 (1960) 1–44.

[17] T.D. Crocker, The structuring of atmospheric pollution control systems, The Economics of Air Pollution 61 (1966) 81–84.

[18] W.R.D. Sewell, J. H. Dales, Pollution, Property & Prices: An Essay in Policy-making and Economics. Toronto: University of Toronto Press, 1968, pp. vii, 111., Canadian Journal of Political Science/Revue Canadienne de Science Politique 2 (1969) 386–387. https://doi.org/DOI: 10.1017/S0008423900025282.

[19] G. Hardin, The tragedy of the commons, American Association for the Advancement of Science, 2018. https://doi.org/10.1201/9781351071765.

[20] U. Boesen, Excise Tax Application and Trends, Taxfoundation.Org (2021). https://taxfoundation.org/research/all/federal/excise-taxes-excise-tax-trends/ (accessed October 10, 2023).

[21] The World Bank, State and Trends of Carbon Pricing 2022, 2022. https://doi.org/10.1596/978-1-4648-1895-0. License: Creative Commons Attribution CC BY 3.0 IGO.

[22] The World Bank, State and Trends of Carbon Pricing 2023, n.d.

[23] European Commission, ‘Fit for 55’: delivering the EU’s 2030 climate target on the way to climate neutrality. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, (2021).

[24] Carbon Market Watch, Pricing carbon to achieve the Paris goals, 2017.

[25] International Carbon Action Partnership, (2023). https://icapcarbonaction.com/en/ets-prices (accessed October 27, 2023).

[26] J.-F. Morin, J. Allan, S. Jinnah, The survival of the weakest: the echo of the Rio Summit principles in environmental treaties, Env Polit (2023) 1–22. https://doi.org/10.1080/09644016.2023.2236505.

[27] United Nations Framework Convention on Climate Change, The Kyoto Protocol to the United Nations Convention on Climate Change, (1997).

[28] Change United Nations Framework Convention on Climate, Kyoto Protocol to the United Nations Framework Convention on Climate Change: Annex B, (2008).

[29] S.F. Verde, S. Borghesi, The International Dimension of the EU Emissions Trading System: Bringing the Pieces Together, Environ Resour Econ (Dordr) 83 (2022) 23–46. https://doi.org/10.1007/s10640-022-00705-x.

[30] I. Shishlov, R. Morel, V. Bellassen, Compliance of the Parties to the Kyoto Protocol in the first commitment period, Climate Policy 16 (2016) 768–782. https://doi.org/10.1080/14693062.2016.1164658.

[31] D. Bodansky, The legal character of the Paris agreement, Rev Eur Comp Int Environ Law 25 (2016) 142–150. https://doi.org/10.1111/reel.12154.

[32] A. Marcu, Governance of Article 6 of the Paris Agreement and Lessons Learned from the Kyoto Protocol, Centre for International Governance Innovation (2017).

[33] A. Marcu, Carbon Market Provisions in the Paris Agreement (Article 6), CEPS Report (2016).

[34] European Commission, EU ETS Handbook, 2015.

[35] OECD, Emission trading systems, OECD.Org (2023). https://www.oecd.org/env/tools-evaluation/emissiontradingsystems.htm (accessed September 15, 2023).

[36] OECD, Interactions Between Emission Trading Systems and Other Overlapping Policy Instruments, 2011.

[37] J. Teixidó, S.F. Verde, F. Nicolli, The impact of the EU Emissions Trading System on low-carbon technological change: The empirical evidence, Ecological Economics 164 (2019) 106347. https://doi.org/https://doi.org/10.1016/j.ecolecon.2019.06.002.

[38] L. Haywood, M. Jakob, The role of the emissions trading scheme 2 in the policy mix to decarbonize road transport in the European Union, Transp Policy (Oxf) 139 (2023) 99–108. https://doi.org/https://doi.org/10.1016/j.tranpol.2023.06.003.

[39] Report from the Commission to the European parliament and the Council on the functioning of the European carbon market in 2021, 2022.

[40] Development of EU ETS (2005-2020), (2022). https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/development-eu-ets-2005-2020_en (accessed October 21, 2023).

[41] The World Bank, State and Trends of Carbon Pricing 2021, 2021.

[42] A. Zaklan, J. Wachsmuth, V. Duscha, The EU ETS to 2030 and beyond: adjusting the cap in light of the 1.5°C target and current energy policies, Climate Policy 21 (2021) 778–791. https://doi.org/10.1080/14693062.2021.1878999.

[43] V. Azarova, M. Mier, Market Stability Reserve under exogenous shock: The case of COVID-19 pandemic, Appl Energy 283 (2021) 116351. https://doi.org/https://doi.org/10.1016/j.apenergy.2020.116351.

[44] S. Borghesi, A. Ferrari, Social impact of Emissions Trading Systems – Auction revenues and social expenditures in a changing world, European University Institute, 2022. https://doi.org/doi/10.2870/451676.

[45] European Environment Agency, Use of auctioning revenues generated under the EU Emissions Trading System, (2023). https://www.eea.europa.eu/en/analysis/indicators/use-of-auctioning-revenues-generated?activeAccordion=546a7c35-9188-4d23-94ee-005d97c26f2b (accessed October 24, 2023).

[46] M.J. Dorsch, C. Flachsland, U. Kornek, Building and enhancing climate policy ambition with transfers: allowance allocation and revenue spending in the EU ETS, Env Polit 29 (2020) 781–803. https://doi.org/10.1080/09644016.2019.1659576.
[47] E. Krause, A. Roth, M. Schäfer, Using carbon pricing revenues for social compensation, 2022.
[48] J. Jaraitė, C. Di Maria, Did the EU ETS Make a Difference? An Empirical Assessment Using Lithuanian Firm-Level Data, The Energy Journal 37 (2016) 1–23. http://www.jstor.org/stable/24696699.
[49] R. Calel, Adopt or Innovate: Understanding Technological Responses to Cap-and-Trade, Am Econ J Econ Policy 12 (2020) 170–201. https://doi.org/10.1257/pol.20180135.
[50] J. Colmer, R. Martin, M. Muûls, U.J. Wagner, Does Pricing Carbon Mitigate Climate Change? Firm-Level Evidence from the European Union Emissions Trading Scheme, SSRN Electronic Journal (2020). https://doi.org/10.2139/ssrn.3725482.
[51] P. Bayer, M. Aklin, The European Union Emissions Trading System reduced CO2 emissions despite low prices, Proceedings of the National Academy of Sciences 117 (2020) 8804–8812. https://doi.org/10.1073/pnas.1918128117.
[52] X. Fageda, J.J. Teixidó, Pricing carbon in the aviation sector: Evidence from the European emissions trading system, J Environ Econ Manage 111 (2022) 102591. https://doi.org/10.1016/j.jeem.2021.102591.
[53] C. Flachsland, M. Pahle, D. Burtraw, O. Edenhofer, M. Elkerbout, C. Fischer, O. Tietjen, L. Zetterberg, How to avoid history repeating itself: the case for an EU Emissions Trading System (EU ETS) price floor revisited, Climate Policy 20 (2020) 133–142. https://doi.org/10.1080/14693062.2019.1682494.
[54] L. A. Greening, D.L. Greene, C. Difiglio, Energy efficiency and consumption — the rebound effect — a survey, Energy Policy 28 (2000) 389–401. https://doi.org/10.1016/S0301-4215(00)00021-5.
[55] M. Chitnis, S. Sorrell, A. Druckman, S.K. Firth, T. Jackson, Turning lights into flights: Estimating direct and indirect rebound effects for UK households, Energy Policy 55 (2013) 234–250. https://doi.org/10.1016/j.enpol.2012.12.008.
[56] N.K. Ghosh, M.F. Blackhurst, Energy savings and the rebound effect with multiple energy services and efficiency correlation, Ecological Economics 105 (2014) 55–66. https://doi.org/10.1016/j.ecolecon.2014.05.002.
[57] J. Freire-González, A new way to estimate the direct and indirect rebound effect and other rebound indicators, Energy 128 (2017) 394–402. https://doi.org/10.1016/j.energy.2017.04.057.
[58] J. Zhang, C.-Y.C. Lin Lawell, The macroeconomic rebound effect in China, Energy Econ 67 (2017) 202–212. https://doi.org/10.1016/j.eneco.2017.08.020.
[59] C.K. Bolat, U. Soytas, B. Akinoglu, S. Nazlioglu, Is there a macroeconomic carbon rebound effect in EU ETS?, Energy Econ 125 (2023) 106879. https://doi.org/10.1016/j.eneco.2023.106879.
[60] A. Dechezleprêtre, D. Nachtigall, F. Venmans, The joint impact of the European Union emissions trading system on carbon emissions and economic performance, J Environ Econ Manage 118 (2023) 102758. https://doi.org/10.1016/j.jeem.2022.102758.
[61] W. Rickels, A. Proelß, O. Geden, J. Burhenne, M. Fridahl, Integrating Carbon Dioxide Removal Into European Emissions Trading, Frontiers in Climate 3 (2021). https://doi.org/10.3389/fclim.2021.690023.
[62] J. Böning, V. Di Nino, T. Folger, Benefits and Costs of the ETS in the EU, a Lesson Learned for the CBAM Design, SSRN Electronic Journal (2023). https://doi.org/10.2139/ssrn.4335984.
[63] FSR Climate, A literature-based assessment of the EU ETS, 2019.
[64] A. Antoci, S. Borghesi, G. Iannucci, M. Sodini, Should I stay or should I go? Carbon leakage and ETS in an evolutionary model, Energy Econ 103 (2021). https://doi.org/10.1016/j.eneco.2021.105561.
[65] M. Kopel, F. Lamantia, F. Szidarovszky, Evolutionary competition in a mixed market with socially concerned firms, J Econ Dyn Control 48 (2014) 394–409. https://doi.org/https://doi.org/10.1016/j.jedc.2014.06.001.
[66] S. Chen, D. Marbouh, S. Moore, K. Stern, Voluntary Carbon Offsets: An Empirical Market Study, SSRN Electronic Journal (2021). https://doi.org/10.2139/ssrn.3981914.

[67] Derik Broekhoff, Michael Gillenwater, Tani Colbert-Sangree, Patrick Cage, Securing Climate Benefit: A Guide to Using Carbon Offsets, 2020. https://www.offsetguide.org/wp-content/uploads/2020/03/Carbon-Offset-Guide_3122020.pdf (accessed November 12, 2023).

[68] Kelley Hamrick, Allie Goldstein, Ahead of the curve. State of the Voluntary Carbon Markets in 2015., 2015. https://www.forest-trends.org/wp-content/uploads/2015/06/State-of-the-Voluntary-Carbon-Markets-2015.pdf.

[69] South Pole, The Voluntary Carbon Market | 2022-2023, 2023.

[70] R. Bayon, A. Hawn, K. Hamilton, Voluntary carbon markets, 2nd ed., Routledge, London, England, 2012. https://doi.org/10.4324/9781849773737.

[71] D.-H. Lee, D. Kim, S. Kim, Characteristics of forest carbon credit transactions in the voluntary carbon market, Climate Policy 18 (2018) 235–245. https://doi.org/10.1080/14693062.2016.1277682.

[72] Task Force on scaling Voluntary Carbon Markets, (2023). https://www.iif.com/tsvcm (accessed November 20, 2023).

[73] Tim Adams, Bill Winters, Annette Nazaret, Taskforce on scaling voluntary Carbon Markets , 2021. https://www.iif.com/Portals/1/Files/TSVCM_Report.pdf.

[74] J.A. Foley, R. DeFries, G.P. Asner, C. Barford, G. Bonan, S.R. Carpenter, F.S. Chapin, M.T. Coe, G.C. Daily, H.K. Gibbs, J.H. Helkowski, T. Holloway, E.A. Howard, C.J. Kucharik, C. Monfreda, J.A. Patz, I.C. Prentice, N. Ramankutty, P.K. Snyder, Global Consequences of Land Use, Science (1979) 309 (2005) 570–574. https://doi.org/10.1126/science.1111772.

[75] M.-K. Kim, B.A. McCarl, B.C. Murray, Permanence discounting for land-based carbon sequestration, Ecological Economics 64 (2008) 763–769. https://doi.org/10.1016/j.ecolecon.2007.04.013.

[76] M. Wang, B. McCarl, H. Wei, L. Shiva, Unintended Consequences of Agricultural Participation in Voluntary Carbon Markets: Their Nature and Avoidance, Complexity 2021 (2021) 1–17. https://doi.org/10.1155/2021/9518135.

[77] S. La Hoz Theuer, M. Hall, A. Eden, E. Krause, C. Haug, S. De Clara, Offset Use Across Emissions Trading Systems, Berlin, 2023.

[78] T.A.P. West, S. Wunder, E.O. Sills, J. Börner, S.W. Rifai, A.N. Neidermeier, G.P. Frey, A. Kontoleon, Action needed to make carbon offsets from forest conservation work for climate change mitigation, Science (1979) 381 (2023) 873–877. https://doi.org/10.1126/science.ade3535.

[79] T.A.P. West, J. Börner, E.O. Sills, A. Kontoleon, Overstated carbon emission reductions from voluntary REDD+ projects in the Brazilian Amazon, Proceedings of the National Academy of Sciences 117 (2020) 24188–24194. https://doi.org/10.1073/pnas.2004334117.

[80] H. Wang-Helmreich, N. Kreibich, The potential impacts of a domestic offset component in a carbon tax on mitigation of national emissions, Renewable and Sustainable Energy Reviews 101 (2019) 453–460. https://doi.org/https://doi.org/10.1016/j.rser.2018.11.026.

[81] M.N. CONTE, M.J. KOTCHEN, EXPLAINING THE PRICE OF VOLUNTARY CARBON OFFSETS, Clim Chang Econ (Singap) 01 (2010) 93–111. https://doi.org/10.1142/S2010007810000091.

[82] Maria Eugenia Filmanovic, Carbon credits prices in the voluntary carbon market. Abatable., (2022). https://www.abatable.com/blog/carbon-credits-pricing (accessed February 27, 2024).

[83] Gold Standard, CARBON PRICING: Why do prices vary by project type?, (2016). https://www.goldstandard.org/blog-item/carbon-pricing-why-do-prices-vary-project-type (accessed February 27, 2024).

[84] S. Donofrio, Procton Alex, Ecosystem marketplace insights report. Paying for quality. State of Voluntary Carbon Markets in 2023., 2023. https://www.ecosystemmarketplace.com/publications/state-of-the-voluntary-carbon-markets-2021/.

[85] M. sultana Choudhury, J. Phillips, S. Favasuli, S. Vandana, Commodities 2024: Price slump in 2023 clouds outlook for voluntary carbon market. S&P Global., (2024).

[86] C. Blaudelder, C. Levy, P. Mannion, D. Pinner, A blueprint for scaling voluntary carbon markets to meet the climate challenge. Mckinsey Sustainability, (2021).

https://www.mckinsey.com/capabilities/sustainability/our-insights/a-blueprint-for-scaling-voluntary-carbon-markets-to-meet-the-climate-challenge.

[87] IEA, CO2 Emissions in 2022, 2023. https://iea.blob.core.windows.net/assets/3c8fa115-35c4-4474-b237-1b00424c8844/CO2Emissionsin2022.pdf.

[88] IEA, Renewable Energy Market Update, 2023. https://www.iea.org/reports/renewable-energy-market-update-june-2023.

[89] D. Chiaramonti, G. Talluri, The future of Sustainable Biofuels towards the 2°C target: forecasting process, technologies and sector demands, E3S Web of Conferences 238 (2021) 08002. https://doi.org/10.1051/e3sconf/202123808002.

[90] European Court of Auditors, The EU's support for sustainable biofuels in transport. An unclear route ahead., 2023. https://www.eca.europa.eu/ECAPublications/SR-2023-29/SR-2023-29_EN.pdf.

[91] IEA, Biofuels, (2023). https://www.iea.org/energy-system/low-emission-fuels/biofuels (accessed November 20, 2023).

[92] IEA, Net Zero by 2050, 2021. https://www.iea.org/reports/net-zero-by-2050.

[93] GSE, Energia nel settore dei trasporti. 2005-2021., n.d.

[94] D. Chiaramonti, G. Talluri, The future of Sustainable Biofuels towards the 2°C target: forecasting process, technologies and sector demands, E3S Web of Conferences 238 (2021) 08002. https://doi.org/10.1051/e3sconf/202123808002.

[95] O. Hurtig, M. Buffi, N. Scarlat, V. Motola, A. Georgakaki, S. Letout, A. Mountraki, G. Joanny Ordonez, Clean Energy Technology Observatory: Advanced Biofuels in the European Union ? 2022 Status Report on Technology Development, Trends, Value Chains and Markets , Publications Office of the European Union, Luxembourg (Luxembourg), 2022. https://doi.org/10.2760/938743 (online).

[96] IEA, Energy Technology Perspectives 2020, 2020. https://iea.blob.core.windows.net/assets/7f8aed40-89af-4348-be19-c8a67df0b9ea/Energy_Technology_Perspectives_2020_PDF.pdf.

[97] IEA, Phasing Out Unabated Coal, 2021. https://iea.blob.core.windows.net/assets/861dc94d-a684-4875-80fb-a1faaf914125/PhasingOutUnabatedCoal-CurrentStatusandThreeCaseStudies.pdf.

[98] IEA, Energy Technology Perspectives 2020 - CCUS in clean energy transitions., 2020. https://iea.blob.core.windows.net/assets/181b48b4-323f-454d-96fb-0bb1889d96a9/CCUS_in_clean_energy_transitions.pdf.

[99] IEA, Direct Air Capture, 2022. https://iea.blob.core.windows.net/assets/78633715-15c0-44e1-81df-41123c556d57/DirectAirCapture_Akeytechnologyfornetzero.pdf.

[100] L. Jiang, W. Liu, R.Q. Wang, A. Gonzalez-Diaz, M.F. Rojas-Michaga, S. Michailos, M. Pourkashanian, X.J. Zhang, C. Font-Palma, Sorption direct air capture with CO2 utilization, Prog Energy Combust Sci 95 (2023) 101069. https://doi.org/https://doi.org/10.1016/j.pecs.2022.101069.

[101] M. Fasihi, O. Efimova, C. Breyer, Techno-economic assessment of CO2 direct air capture plants, J Clean Prod 224 (2019) 957–980. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.03.086.

[102] N. McQueen, K.V. Gomes, C. McCormick, K. Blumanthal, M. Pisciotta, J. Wilcox, A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future, Progress in Energy 3 (2021) 032001. https://doi.org/10.1088/2516-1083/abf1ce.

[103] Climeworks launches direct air capture plant in Italy, (2020). https://climeworks.com/news/climeworks-launches-dac-3-plant-in-italy (accessed December 10, 2023).

[104] Direct Air Capture (DAC) appliances, Hydrocell Ltd. (2018). https://hydrocell.fi/en/air-cleaners-carbon-dioxide-filters-and-dac-appliances/dac-appliances/ (accessed December 10, 2023).

[105] Skytree, (2018). https://www.skytree.eu/ (accessed December 10, 2023).

[106] Infinitree, (2018). http://www.infinitreellc.com/technology/ (accessed December 10, 2023).

[107] Aker Carbon Capture, (2023). https://akercarboncapture.com/about-us/key-projects/ (accessed December 10, 2023).

[108] M. Ozkan, S.P. Nayak, A.D. Ruiz, W. Jiang, Current status and pillars of direct air capture technologies, IScience 25 (2022) 103990. https://doi.org/https://doi.org/10.1016/j.isci.2022.103990.

[109] M. Ozkan, Direct air capture of CO2: A response to meet the global climate targets, MRS Energy & Sustainability 8 (2021) 51–56. https://doi.org/10.1557/s43581-021-00005-9.

[110] D.W. Keith, G. Holmes, D. St. Angelo, K. Heidel, A Process for Capturing CO2 from the Atmosphere, Joule 2 (2018) 1573–1594. https://doi.org/https://doi.org/10.1016/j.joule.2018.05.006.

[111] J. Hammond, S. Shackley, S. Sohi, P. Brownsort, Prospective life cycle carbon abatement for pyrolysis biochar systems in the UK, Energy Policy 39 (2011) 2646–2655. https://doi.org/https://doi.org/10.1016/j.enpol.2011.02.033.

[112] J. Lehmann, A handful of carbon, Nature 447 (2007) 143–144. https://doi.org/10.1038/447143a.

[113] J.W. Lee, B. Hawkins, D.M. Day, D.C. Reicosky, Sustainability: the capacity of smokeless biomass pyrolysis for energy production, global carbon capture and sequestration, Energy Environ Sci 3 (2010) 1695. https://doi.org/10.1039/c004561f.

[114] J. Lehmann, M.C. Rillig, J. Thies, C.A. Masiello, W.C. Hockaday, D. Crowley, Biochar effects on soil biota – A review, Soil Biol Biochem 43 (2011) 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022.

[115] R.K. Shrestha, P.A. Jacinthe, R. Lal, K. Lorenz, M.P. Singh, S.M. Demyan, W. Ren, L.E. Lindsey, Biochar as a negative emission technology: A synthesis of field research on greenhouse gas emissions, J Environ Qual 52 (2023) 769–798. https://doi.org/10.1002/jeq2.20475.

[116] A. Dufour, Geological Sequestration of Biomass Char to Mitigate Climate Change, Environ Sci Technol (2013) 130829114030003. https://doi.org/10.1021/es4036418.

[117] European Biochar Market Report 2022|2023, 2023. https://www.biochar-industry.com/wp-content/uploads/2023/03/European-Biochar-Market-Report_20222023.pdf (accessed December 20, 2023).

[118] S. Fawzy, A.I. Osman, N. Mehta, D. Moran, A.H. Al-Muhtaseb, D.W. Rooney, Atmospheric carbon removal via industrial biochar systems: A techno-economic-environmental study, J Clean Prod 371 (2022). https://doi.org/10.1016/j.jclepro.2022.133660.

[119] D. Lefebvre, S. Fawzy, C.A. Aquije, A.I. Osman, K.T. Draper, T.A. Trabold, Biomass residue to carbon dioxide removal: quantifying the global impact of biochar, Biochar 5 (2023) 65. https://doi.org/10.1007/s42773-023-00258-2.

[120] D. Woolf, J. Lehmann, S. Ogle, A.W. Kishimoto-Mo, B. McConkey, J. Baldock, Greenhouse Gas Inventory Model for Biochar Additions to Soil, Environ Sci Technol 55 (2021) 14795–14805. https://doi.org/10.1021/acs.est.1c02425.

[121] J. Jian, M.K. Steele, L. Zhang, V.L. Bailey, J. Zheng, K.F. Patel, B.P. Bond-Lamberty, On the use of air temperature and precipitation as surrogate predictors in soil respiration modelling, Eur J Soil Sci 73 (2022) e13149. https://doi.org/https://doi.org/10.1111/ejss.13149.

[122] M.W. Jones, G.P. Peters, T. Gasser, R.M. Andrew, C. Schwingshackl, J. Gütschow, R.A. Houghton, P. Friedlingstein, J. Pongratz, C. Le Quéré, National contributions to climate change due to historical emissions of carbon dioxide, methane, and nitrous oxide since 1850, Sci Data 10 (2023) 155. https://doi.org/10.1038/s41597-023-02041-1.

[123] N. Scarlat, F. Fahl, E. Lugato, F. Monforti-Ferrario, J.F. Dallemand, Integrated and spatially explicit assessment of sustainable crop residues potential in Europe, Biomass Bioenergy 122 (2019) 257–269. https://doi.org/https://doi.org/10.1016/j.biombioe.2019.01.021.

[124] L. Pari, V. Alfano, D. Garcia-Galindo, A. Suardi, E. Santangelo, Pruning Biomass Potential in Italy Related to Crop Characteristics, Agricultural Practices and Agro-Climatic Conditions, Energies (Basel) 11 (2018) 1365. https://doi.org/10.3390/en11061365.

[125] S.K. Thengane, K. Kung, R. York, S. Sokhansanj, C.J. Lim, D.L. Sanchez, Technoeconomic and emissions evaluation of mobile in-woods biochar production, Energy Convers Manag 223 (2020) 113305. https://doi.org/10.1016/j.enconman.2020.113305.

[126] Y. Gao, G. Shao, Z. Yang, K. Zhang, J. Lu, Z. Wang, S. Wu, D. Xu, Influences of soil and biochar properties and amount of biochar and fertilizer on the performance of biochar in improving plant photosynthetic rate: A meta-analysis, European Journal of Agronomy 130 (2021) 126345. https://doi.org/10.1016/j.eja.2021.126345.

[127] A. Pinzuti, Biochar: Analysis and Economic Potential with a Focus on European Producers, Politecnico di Torino, 2023. https://webthesis.biblio.polito.it/28436/1/tesi.pdf (accessed March 19, 2024).