POLITECNICO DI TORINO

Master’s degree programme
in Energy and Nuclear Engineering

Carbon Capture and Storage (CCS): Technical and economic review of dealing with CO_2 in Europe and Australia

Supervisors:
Prof. Alexander Klimenko
Prof. Glenda Taddia
Prof. Dario Viberti

Candidate
Alessio Faloci

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ABSTRACT

This thesis aims to provide the reader with an overview of climate change caused by the greenhouse effect by analysing policies and strategies adopted by countries, both presently and historically, with a focus on the situations in Europe and Australia. The main character of the work is going to be introduced, the CO_2, and one of the main method to deal with it is deeply discussed and evaluated in detail: the Carbon Pricing. Following this, comparisons among countries are made, highlighting differences and calculating key performance indicators to determine which country has been the most polluting both currently and historically. The goal of the study is to analyse one potential solution to reduce CO_2 emissions: Carbon Capture and Storage (CCS) technology. This technology is explained, and an overview of CCS plants in Europe and Australia is provided. The outcomes include the calculation of two main parameters: the cost of CCS plants and their storage capacity. Finally, these are compared with the price of carbon emissions and current emission levels in Australia and Europe. The results underscore the theoretical feasibility of CCS in terms of available storage sites. However, the cost remains a limiting factor for this technology, particularly in the case of Australia, where it may currently be cheaper to pay for emissions than to store them. Fortunately, the price of CO_2 emissions has been increasing in recent years, suggesting that the cost of CCS, along with its widespread implementation and associated investments, may decrease, creating favourable conditions for the adoption of this technology.

INTRODUCTION

This thesis work aims to provide the reader a deep understanding of climate change, policies and strategies that countries are adopting against it (e.g. European Green Deal, the largest package of policy initiatives against climate change so far). In particular the study is focused on greenhouse effect and the main cause of it, the carbon dioxide. It is going to explore the current methodologies that countries are using to reduce CO_2 emissions (e.g. Carbon Pricing) and possible solutions. The final outcome of the study is to evaluate the feasibility of one particular method, Carbon Capture and Storage. It is going to do that by analysing both technical and economic parameters of the CCS. The majority of the data in this work are related to two areas, Australia and Europe, respectively the location of the host university during the thesis work and the location of the university where the thesis is going to be discussed.

First of all we tried to analyse the causes of greenhouse effect on our planet and reviewed the measures adopted from countries around the world during the past. In particular all the main past meetings against climate changes and their main outcomes are described at the beginning. After that it focuses on the current situation in terms of legislative obligations and adopted strategies. Here, the European Green Deal and the Australian Climate Change Act are explained and discussed.

Following that, a widespread and useful methodology that is currently used against GHGs is explained in detail. It is helping a lot especially Europe but also other countries to fight against greenhouse gas emissions and it is called "Carbon Pricing". We give to the reader an explanation of different Carbon Pricing methods available, a comparison between them and the factors that can influence their patterns over the time. Carbon Pricing mechanisms for Europe and Australia are deeply analysed with all of their incomes, goals and structures.

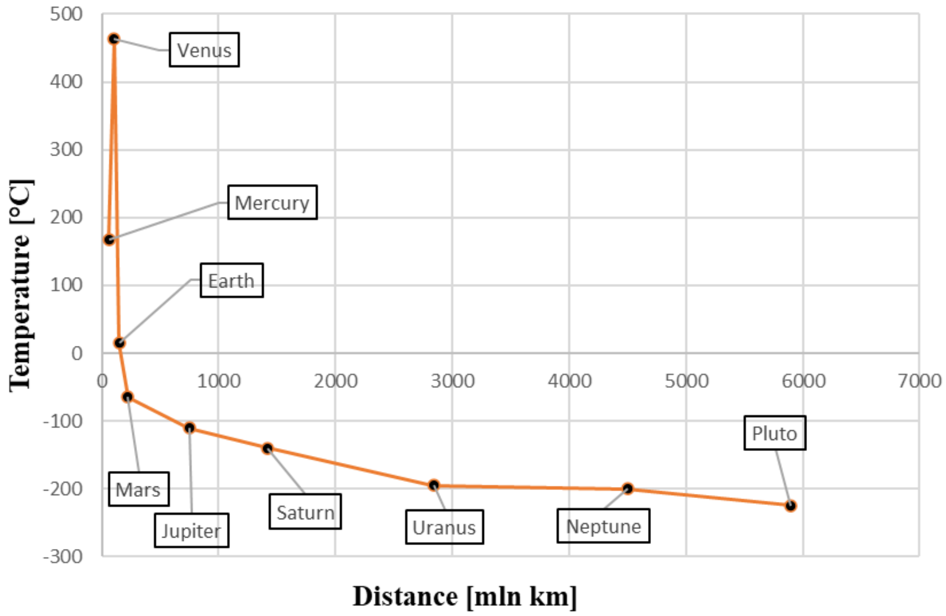
Subsequently a focus has been done on CO_2, the main character when we talk about greenhouse gases. A big chapter is dedicated to this gas where it is introduced and it is also explained why it is considered so important among GHGs. Moreover, there are many interested data comparisons among countries to properly understand whose fault is it and to establish who pollutes less.

Starting from chapter five there is the beginning of Carbon Capture and Storage review. It is proposed as a solution that can help us with current targets and situation. The beginning phases of Capture and Transport are briefly explained here. After that the focus is shifted on Storage, the main topic of our review. It is explained in depth, from the physic principles behind it to the different storage locations currently used. Furthermore it is also proposed a new promising method currently used only in one plant in Iceland that is still under development. It uses a particular methods both for capturing and storing the carbon dioxide. After that the work describes also the operational CCS plants in Europe and Australia with their main parameters, purposes and contexts.

Finally we tried to understand if the CCS could be a good ally to climate change fight against greenhouse gas. We did it through the estimation of two main parameters that are the storage capacity and the costs of CCS in Europe and Australia. These ones has been compared with current emissions and carbon prices to understand if CCS in those countries is feasible. Thanks to the first comparison we were able to determine for how many years we can ideally continue to store CO_2. Secondly, if we consider stored emissions as not emitted (this is how the law works) through the second comparison we properly understand if for a company it is convenient to invest into CCS technologies or if it is better to pay for their emissions.

1) GREENHOUSE EFFECT

The fact that Earth has an average surface temperature pleasurably between the boiling point and freezing point of water (15[°C]) (1), therefore suitable for our kind of life, cannot be clarified by merely proposing that planet Earth orbits at just the precise space from the sun to absorb just the right amount of solar radiation. The moderate temperatures are also the outcome of having just the precise kind of atmosphere.



Graph 1. Average temperature of planets in the Solar System (1).

As we can see from “graph 1” the temperature of a planet’s surface is not directly proportional to the distance from the sun and a planet closer to the sun could have a temperature lower than one further (e.g. Venus and Mercury).

Parts of the earth’s atmosphere act as shielding blanket of just the right thickness, receiving appropriate solar energy to keep the global average temperature in an amusing range. This blanket is composed of what we called greenhouse gases. They are called in this way because they act as the glass walls of a greenhouse. Incoming ultra violet radiation (10^{-8} [m] wavelength) from the sun easily passes through the atmosphere gases and is absorbed by the surface of the earth. Then the heat is emitted from the earth in form of infrared radiation (10^{-5} [m] wavelength), however, it has difficulty passing through the atmosphere and a part of it is reflected to the earth or absorbed from the gases, this cause the warming of the surface (2).

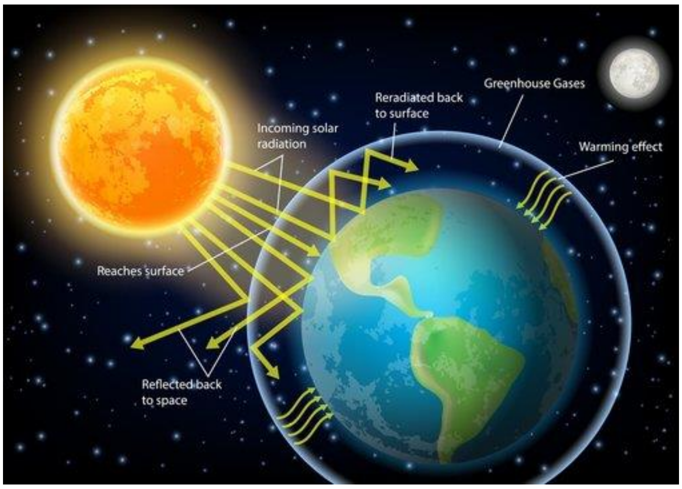


Figure 1. Greenhouse effect (3)

The greenhouse effect is a foremost factor in keeping the Earth heartfelt because it keeps some of the planet's heat that would otherwise escape from the atmosphere out to space. In fact, without the greenhouse effect the Earth's average global temperature would be much colder and life on Earth as we recognize it would not be possible. The expected average surface temperature of the earth would be -19 [°C] just the Sun’s radiation (4), about 30 [°C] less than the current one. The greenhouse effect was first discovered by Joseph Fourier in 1827, experimentally verified by John Tyndall in 1861, and quantified by Svante Arrhenius in 1896 (5). The main problem is related to the alteration of the greenhouse gases layer in our atmosphere due to anthropologic activities that cannot be balanced by natural phenomena and leads to the rise of the average surface temperature. The causes of the enhancement of the greenhouse effect are as follows: industries and energy production - nowadays these sectors still rely a lot on fossil fuels as coal, oil and natural gas. When they are burned they produce a huge amount of carbon dioxide and other greenhouse gases; means of transportation - in the world the majority of materials are transported through ships, airplanes, trucks and train and generally they use fossil fuels. Furthermore we should take into account the deforestation and habitat destruction - the plants are one of ours biggest allies against climate change, due to the fact that for their lifecycle they absorb carbon dioxide. Intensive use of wood for human products or deforestation for intensive crops reduces the presence of forests and then the CO_2 absorbed from the nature. Moreover, the increase in population affects the growing demand for food, clothing, housing - all this activities rely on industrials mainly based on fossil fuels, therefore the outcome is an increasing in greenhouse gases production. Also the fertilizers we use in agro-chemistry have nitrogen inside – when they evaporate this molecule is released and it is a greenhouse gas. Finally the most used method for garbage treatment is burning them through incinerator by producing GHSs (6).

2) CLIMATE CHANGE PATHWAY

2.1) A look at the past

During the years there have been concerns about the responsibility of climate change, if it is a natural process or caused by human activities. The **IPCC** (**Intergovernmental Panel on Climate Change**) prepares periodic Assessment Reports about the state of scientific, technical and socio-economic knowledge on climate change, its impacts and future risks, and options for reducing the rate at which climate change is taking place (7). Its periodic reports, particularly the Third Assessment Report (2001) and the Fourth Assessment Report (2007), have provided solid scientific evidence on human responsibility in climate change. If in 2001 it was "probable" that the state of affairs was attributable to human activities, which translated into figures meant between 66 percent and 90 percent, in 2007, the IPCC said that was "very probable" that humans are at fault, which means the probability reached 90 percent (8).

It is possible to retrace the fight against climate changes' pathway through the main conferences and meetings from the beginning to our days:

2.1.1) Stockholm Conference (1972)

The 1972 United Nations Conference on the Human Environment was held in Stockholm. It was the first world meeting that mainly talked about environmental issues. The participants adopted a series of principles for a proper management of the environment as the Stockholm Declaration and Action Plan for the Human Environment and other resolutions (9).

The **Stockholm Declaration**, which contained 26 principles, it is a document that marked the beginning of a dialogue between industrialized and developing countries by underlining the correlations between environmental issues and many society aspects as economy and well being of people.

The **Action Plan** suggested practical ways of acting and contained three main categories:

a) Global Environmental Assessment Programme

b) Environmental management activities;

c) International measures to support assessment and management activities carried out at the national and international levels.

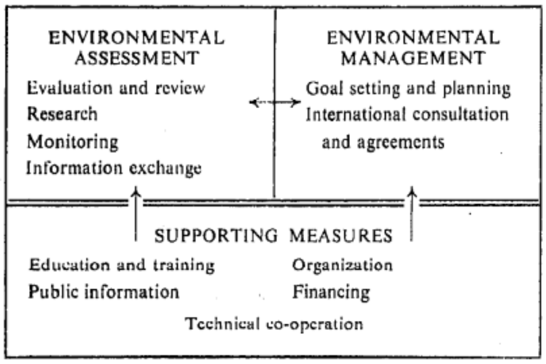


Figure 2. Action plan categories (10).

The biggest outcome of the Stockholm conference was the creation of the United Nations Environment Programme (UNEP) which is the leading global environmental authority setting the global environmental agenda.

In its 50 years of life UNEP has worked together with governments and private entities in order to solve the most hard environmental challenges (as restoring the ozone layer and protect world's seas). UNEP supports 193 member states and their work aim to help countries to achieve a low-carbon and efficient economies, protect ecosystems and strengthening the relations between politic and environmental issue, also through providing evidence-based data on which politicians can make decisions. (11).

2.1.2) Rio De Janeiro Conference (1992)

The second milestone conference in this field was held in Rio De Janeiro on the occasion of the 20th anniversary of the first Human Environment Conference in Stockholm, brought together political leaders, diplomats, scientists, representatives of the media and non-governmental organizations (NGOs) from 179 countries to focus on the impact of human activities on the environment. The main objective of the Rio 'Earth Summit' was to produce a schedule of actions that international governments should have adopted to face global warming.

The main conclusion made by this "Earth Summit" was related to the concept of sustainable development. They said that this is a common goal for all the word, independently on country and level, and it is a necessary requirement for a prosper future. Moreover, it underlined the necessity of integrating between them economic, social and environmental areas, because in order to achieve that goal the are strictly dependent. This is translated into the necessity of change and adapt the way we work, we produce, we consume and also we think before making a decision (12).

One of the major achievements was the creation of the **United Nations Framework Convention on Climate Change** (**UNFCC**). It is a treaty that originally, did not place mandatory limits on greenhouse gas emissions on individual nations; it was therefore legally non-binding. However, it included the possibility for signatory voluntary parties to adopt, at special conferences, additional acts (called "protocols") that would set mandatory emission limits. It already talked about man-made global warming, it said: *"Concerned that human activities have been substantially increasing the atmospheric concentrations of greenhouse gases, that these increases enhance the natural greenhouse effect, and that this will result on average in an additional warming of the Earth's surface and atmosphere and may adversely affect natural ecosystems and humankind"* (13).

2.1.3) Kyoto Protocol (1997) and Doha Amendment (2012)

The Kyoto Protocol was the first international treaty to set legally binding targets to cut greenhouse gas emissions. The agreement was adopted at UN Climate Change Conference (COP 3) in 1997 in Kyoto, entered into force in 2005 and was ratified by 192 Parties, remains a historic landmark in the international fight against climate change. This Protocol has divided the countries of the world into two groups, Annex-I countries comprising of industrialized countries who have historically contributed the most to climate change (43 countries), and non-Annex-I countries, primarily the developing countries. The Kyoto Protocol binds developed countries to reduce their greenhouse gas emission below levels specified for each of them. Each industrialized country has been assigned individual emission reduction targets to reduce the total greenhouse gas emission by at least **5% below the 1990 levels** during the commitment period 2008-2012. To enable countries to meet their emissions reduction targets, the Kyoto Protocol established three market-based mechanisms: Through Emissions Trading, countries have a emissions limit that they cannot exceed, if they are under it they can sell their amount to the ones that have emitted more. In this way, it becomes economically beneficial to reduce emissions. We talk about this system in a separate chapter. Then there are the Clean Development Mechanism and the Joint Implementation mechanism, thanks to them countries can invest in an emission-reducing project and gain credit points. The Kyoto Protocol also established a rigorous monitoring, review and verification system, as well as a compliance system to ensure transparency and hold Parties to account. Under the Protocol, countries' actual emissions have to be monitored and precise records have to be kept of the trades carried out (14). In the end the United States signed the protocol but did not ratified it and Canada withdrew from it in 2011. For this milestone treaty this was a huge problem, due to the high percentage of emissions that US represented in the past but also in the present.

In Doha, Qatar, on 8 December 2012, the Doha Amendment to the Kyoto Protocol was adopted for a second commitment period, starting in 2013 and lasting until 2020. The Amendment sets a goal of reducing greenhouse gas (GHG) emissions by **18% compared to 1990 levels** for participating countries. It includes new commitments for Annex I Parties to the Kyoto Protocol who agreed to take on commitments in a second commitment period from 1 January 2013 to 31 December 2020 (15).

2.1.4) Paris Agreement (2015)

The last agreement was signed at the UN Climate Change Conference (COP21) in Paris, France, in 2015 and it was adopted by 196 Parties. This time it was signed and ratified also from the US and Canada (The US left the agreement under Trump government in 2017 but they re-entered into the agreement under Biden in 2020). It entered into force in 2016 and it effectively replaced the Kyoto Protocol. Its main purpose is to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels." To limit global warming to 1.5°C, **greenhouse gas emissions must peak before 2025 at the latest and decline 43% by 2030**. Implementation of the Paris Agreement requires economic and social transformation, based on the best available science. Since 2020, countries have been submitting their national climate action plans every 5 years, known as nationally determined contributions (NDCs). They are binding national plan highlighting climate change mitigation, including climate-related targets for greenhouse gas emission reductions. The Paris Agreement invites countries to submit long-term low greenhouse gas emission development strategies (LT-LEDS) for a better understating of their efforts for the long term goal and unlike NDCs they are not mandatory. With the Paris Agreement, countries established an enhanced transparency framework (ETF). Under it, that is going to start in 2024, countries will report transparently all the actions taken and progress in climate change mitigation, adaptation measures and support provided or received. It also provides for international procedures for the review of the submitted reports (16).

2.2) **Present and future outlook**

Nowadays we are still under Paris Agreements. What are the main policy initiatives against climate changes? How are they financed? We are going to have a focus on European Union and Australia current situations.

2.2.1) The European Green Deal

The European Green Deal was officially presented by the European commission in December 2019. It is the largest package of policy initiatives in Europe, which aims to set the EU on the path to a green transition, by reducing greenhouse gas emissions at least of 55% before 2030 with the ultimate goal of reaching climate neutrality by 2050. Its policy initiatives aim to reach the environmental goals by having in parallel a modern and competitive economy. The package includes initiatives covering the climate, the environment, energy, transport, industry, agriculture and sustainable finance, all of which are strongly interlinked.

What are the main initiatives included in the Green Deal?

- **Fit for 55**

  The Fit for 55 package aims to translate the climate ambitions of the Green Deal into law. Its name refers to the EU's target of reducing net greenhouse gas emissions by at least 55% by 2030.

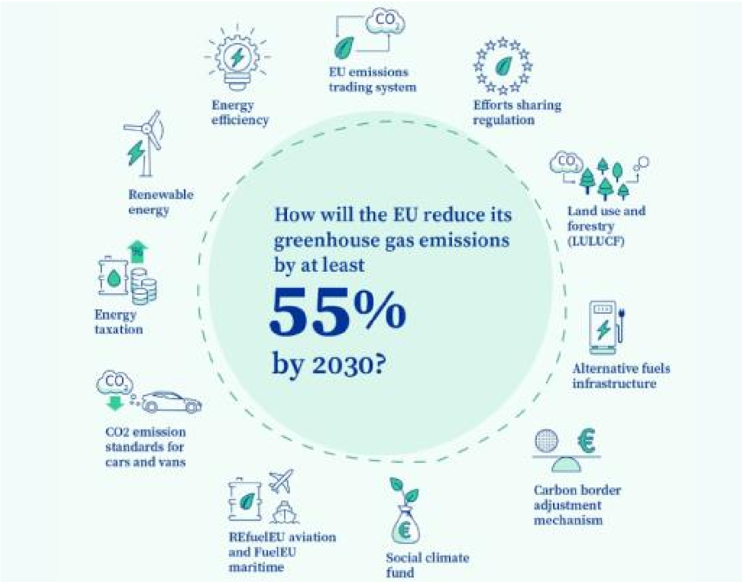


Figure 3. Fit for 55 package initiatives (17).

The package of proposals aims at framework for reaching the EU's climate objectives that has three main principles (17):

- Ensures a just and socially fair transition.
- Maintains and strengthens innovation and competitiveness of EU industry while ensuring a level playing field vis-à-vis third country economic operators.
- Underpins the EU's position as leading the way in the global fight against climate change.

Here some of the main regulations included in this package (Here the ones mainly related to CO_2 direct emissions):

- It evaluate the rules and the operation of the EU Emission Trading System (ETS). Currently it is the main tool that Europe is using against climate change (in terms of emissions reduction). It started in 2005 and works by pricing carbon emissions (see Carbon Pricing chapter for a detailed analysis of it).
- Then the carbon border adjustment mechanism. CBAM targets imports of products in carbon-intensive industries. Its operational is parallel to EU ETS system, because without CBAM EU ETS counts just the emissions inside the borders of member countries. Instead it fights against the relocation of production on non-EU countries. It will gradually replace the existing EU mechanisms to address the risk of carbon leakage, in particular the free allocation of EU ETS allowances.

Figure 4. Carbone leakage (past) (17).

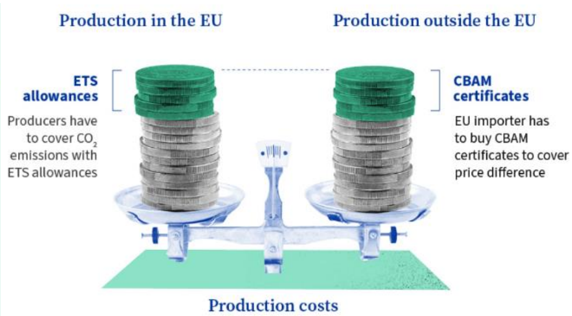


Figure 5. CBAM mechanism (present) (17).

This mechanism currently is adopted and in force (17).

- Removing CO_2 from the atmosphere by capturing it in soil and forests also contributes to reducing the EU's total greenhouse gas emissions. A revision of the LULUCF regulation was approved in March 2023, which sets rules and new ambitious targets for emission reductions and carbon removals in the land use, land use change and forestry (LULUCF). EU forests absorb the equivalent of nearly 10% of total EU greenhouse gas emissions every year. Under the current rules each EU member must ensure that emissions from land use and forestry are compensated by an equivalent removal of CO_2 within the sector. The emissions in this sector are represented mainly by croplands, settlements and grasslands. The new rules set new ambitious target for carbon removal by 2030:

Figure 6. New carbon removal target (17).

There are binding targets for each EU state. This regulation is adopted and in force (17).

- There are some sectors that are not covered by EU ETS and LULUCF systems. For them the effort sharing regulation, last amended in 2018, sets binding annual greenhouse gas emissions targets. These sectors include: road and domestic maritime transport; buildings; agriculture; waste and small industries. They account for 60% of the total EU emissions. The new rules, as part of the Fit for 55 package, will increase the EU-level greenhouse gas emissions reduction target:

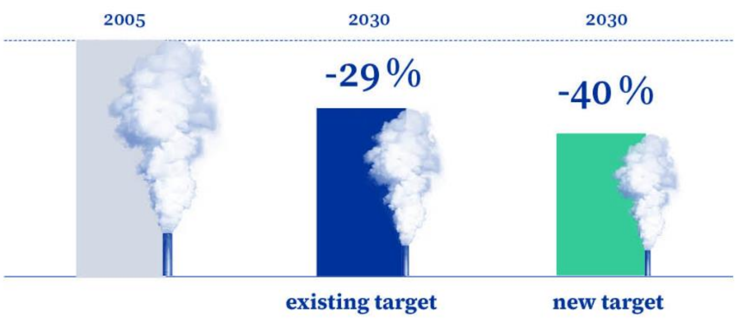


Figure 7. New emissions reduction targets (17).

This regulation was adopted in March 2023 (17).

- CO_2 emission standards for cars and vans. Cars and vans represent still a marked percentage in EU CO_2 emissions. Together they account for 15% of the total EU emissions of carbon dioxide. The proposal introduces progressive EU-wide emissions reduction targets for cars and vans for 2030 and beyond. It sets a 100% reduction target for 2035 for new cars and vans.

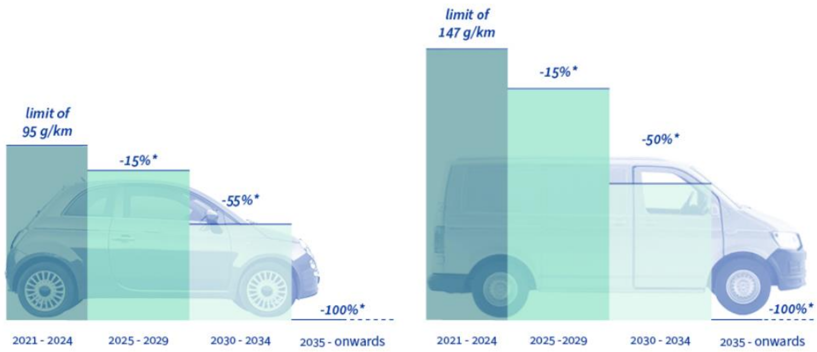


Figure 8. Projected CO_2 emissions reduction for new cars and vans (17).

This regulation was adopted and it is in force (17).

- The energy sector is the main GHGs producer. Therefore a transition to cleaner forms of energy is a cornerstone for climate neutrality. By 2050, most of the energy consumed in the EU will need to come from <u>renewable sources</u>. With Fit for 55 package, the target went from 32% of energy come from renewables in 2030 to 42,5%. In 2022 almost 22% of the energy in EU was renewable, then we need almost to double this share.

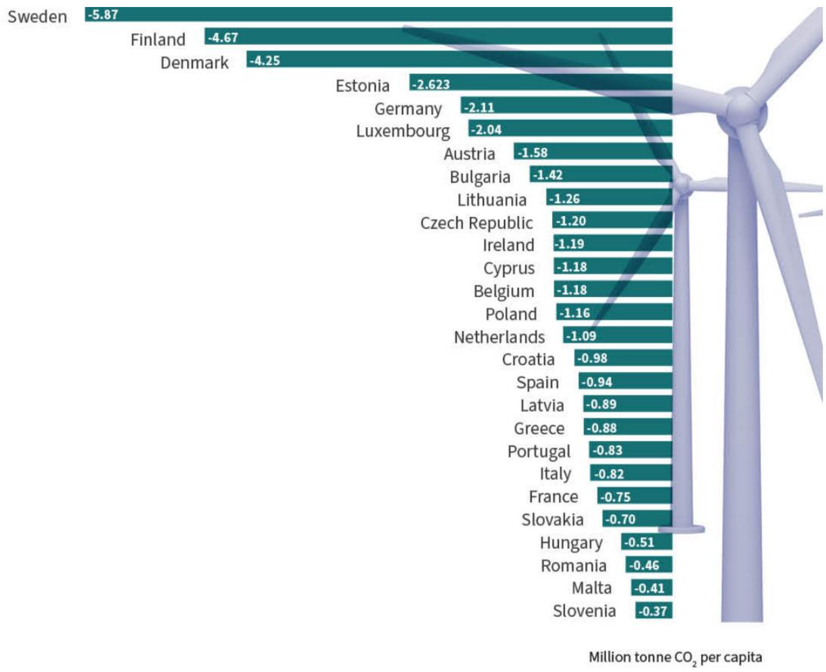


Figure 9. Amount of emissions avoided in EU thanks to renewable energy in 2021 (17).

This regulation was adopted and it is in force (17).

There are many other regulations in the Fit for 55 package, they related to sustainable fuel for aviation and marine sector, reducing methane emissions, increase the energy performance and efficiency in buildings, cutting the use of fossil fuels by switching to renewables fuels as hydrogen and there is also a regulation about taxation on energy products and electricity.

- **European climate law**

  The European climate law regulation turns the political ambition of reaching climate neutrality by 2050 into a legal obligation for the EU. By adopting it, the EU and its member states have a binding agreement of cutting net greenhouse gas emissions in the EU by at least 55% by 2030, compared to 1990 levels. This value was chosen on the base of on an impact assessment carried out by the European Commission. The main actions included in the regulation are (18):

  - Mapping out the pace of emission reductions until 2050 to give predictability to businesses, stakeholders and citizens.
  - Developing a system to monitor and report on the progress made towards the goal.
  - Ensuring a cost-efficient and socially-fair green transition.

- **UE biodiversity strategy for 2030**

  The EU biodiversity strategy for 2030 aims to help recover Europe's biodiversity by 2030. This would bring benefits for people, the climate and the planet. The actions set out in the strategy include (18):

  - Extending protected land and sea areas in Europe.
  - Restoring degraded ecosystems by reducing the use and harmfulness of pesticides.
  - Increasing funding of actions and better monitoring of progress.

- **Farm to fork strategy**

  The Commission's farm to fork strategy aims to help the EU achieve climate neutrality by 2050, by creating a new sustainable model for food, different from the one we have today. In addition to food security and safety, the strategy's main goals are to (18):

  - Ensure sufficient, affordable and nutritious food within planetary limits.
  - Support sustainable food production.
  - Promote more sustainable food consumption and healthy diets.

- **Industrial strategy**

  The importance of EU should be take into account. EU industry accounts for: more than 20% of the EU economy; around 35 million jobs; 80% of the EU's goods exports. With this policy EU aims to create a competitive industry system but at the same time sustainable and digitalized. It relies on industry to lead the transitions towards climate neutrality and digital leadership. The aim is for EU industry to become an accelerator and enabler of change, innovation and growth (18).

- **Circular economy action plan**

  One of the most important plan is decoupling economic growth from resource use. This can be done by shifting to circular systems in production and consumption, and this is key to achieving EU climate neutrality by 2050. The action plan envisages over 30 action points on designing of sustainable products, circularity in production processes and empowering consumers and public buyers. It targets sectors such as electronics and ICT, batteries, packaging, plastics, textiles, construction and buildings, and food (18).

- **Batteries and waste batteries**

  Forecasts for batteries demand expect a grow by more than ten-fold by 2030. In this field create a model based on circular economy is essential and Europe did that by targeting all stages of the life cycle of batteries, from design to waste treatment. This initiative is of major importance, particularly if we take into account the rapid increase of e-mobility. The new regulation adopted in 2023 replaces the current batteries directive of 2006. It aims to both promote a circular economy and improve the functioning of the internal market for batteries ensuring fairer competition thanks to the safety, sustainability and labelling requirements (18).

- **Clean, affordable and secure energy**

  As 75% of EU greenhouse gas emissions come from energy use and production. Then, if we want to achieve the Green Deal goals this sector should be the most important one to be decarbonized. The EU is working at several levels to achieve this objective (18):

  - Supporting the development and uptake of cleaner energy sources, such a renewable offshore energy and hydrogen.
  - Fostering integration of energy systems throughout the EU.
  - Developing interconnected energy infrastructure via EU energy corridors.
  - Revising the current legislation on energy efficiency and renewable energy, including their 2030 targets.

- **Forest strategy and deforestation**

  As we already said, the forests play a crucial role in emissions reduction. The EU forest strategy for 2030, presented by the Commission in July 2021, builds on the EU's biodiversity strategy and forms a key part of efforts to reduce greenhouse gas emissions by at least 55% by 2030. The proposed measures include (18):

- Promoting sustainable forest management.
- Providing financial incentives for forest owners and managers to adopt environmentally friendly practices.
- Improving the size and biodiversity of forests, including by planting 3 billion new trees by 2030.

➢ **EU chemicals strategy for sustainability**

Nowadays the society highly rely on chemical substances for many purposes. Unfortunately they can be harmful for the people and the environment. In March 2021, the Council adopted conclusions endorsing the EU chemicals strategy for sustainability, as presented by the Commission. The strategy sets out a long-term vision for the EU chemicals policy, wherein the EU and member states want to (18):

- Better protect human health.
- Strengthen the industry's competitiveness.
- Support a toxic-free environment.

The strategy is an essential part of the European Green Deal and its zero-pollution ambition.

2.2.2) How is the EU financing the transition

Making the green transition happen and finance all the plans inside EU Green Deal (and there are also others not included in it but related to the transition) will require enormous investment. The EU and its member states have secured over €550 billion for this purpose in the next multiannual budget. The money will be distributed through a number of funds dedicated to different aspects of green transition:

➢ **Social Climate Fund**

Up to €65 billion for 2026-2032 because low-income persons and micro-enterprises may be represent the most impacted businesses due to higher fossil fuel prices resulting from the introduction of a new trading system. The fund is for:

Figure 10. Social Climate Fund (19).

The fund will be financed by the revenues from the auctions of the allowances under this new emissions trading system.

➢ **Just Transition mechanism**

The just transition mechanism provide financial and technical support to the regions most affected by the move towards a low-carbon economy. It will help mobilise at least €55 billion over the period 2021-2027 for: people and communities, companies and member states or regions. With an overall budget of €17.5 billion, the just transition fund is the first financer of the mechanism. It provides tailored support to alleviate the social and economic costs resulting from the green transition for regions dependent on fossil fuels and high-emission industries.

➢ **Modernization fund**

Around €48 billion between 2021 and 2030 is allocated to 10 lower-income member states to be spent on:

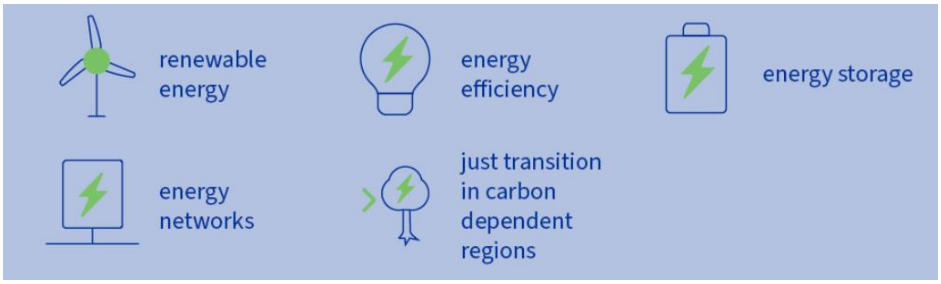


Figure 11. Modernisation fund (19).

The MF is financed through the auctioning of allowances under the EU emissions trading system, in the beginning 2% of the total allowances is being used for the 2021-2030 period.

➢ **Horizon Europe**

€95,5 billion this fund from EU is for research and innovation. 35% of the funds to be spent on climate related projects with these pillars:

Figure 12. Horizon Europe (19).

➢ **Innovation fund**

Around €38 billion between 2020 and 2030 to develop innovative low-carbon technologies, including:

Figure 13. Innovation fund (19).

This fund it is also financed through the auctioning of at least 450 million allowances under the EU ETS.

➢ **Protecting the environment**

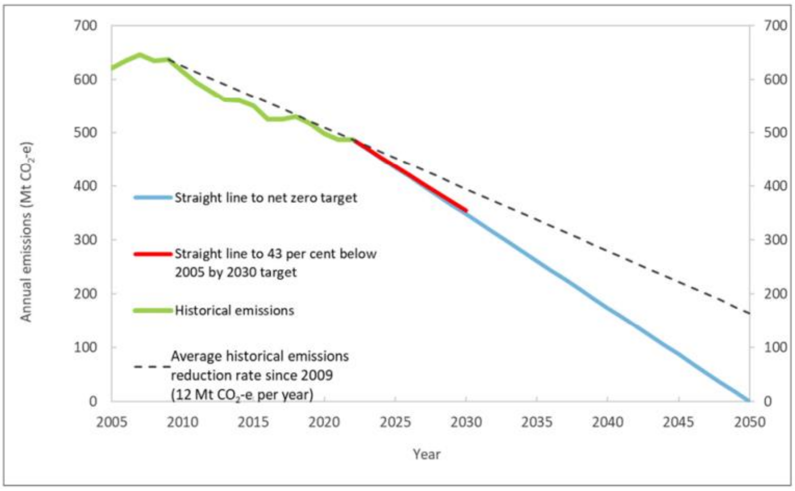
It is a life programme for the environment. 5,5€ billion between 2021 and 2027 to support projects and actions covering:

Figure 14. Protecting the environment (19).

2.2.3) Australia's pathway

In June 2022, the Australian Government submitted a revised 2030 Nationally Determined Contribution (the document required by Paris Agreement), pledging a 43% reduction of greenhouse gas (GHG) emissions by 2030 from 2005 levels, an increase from the previous government's target of 26-28%. This target was legislated alongside the NDC commitment to achieve net zero emissions by 2050 in the **Climate Change Act 2022**.

Australia's point target of reducing emissions by 43 per cent below 2005 levels by 2030 means that Australia is aiming to reduce annual emissions to 354 [Mt CO_{2e}] by 2030. This total is 43 per cent less than emissions in 2005, which were 621.1 [Mt CO_{2e}]. In the year to June 2022, Australia's emissions were 487 [Mt CO_{2e}], meaning annual emissions need to be 133 [Mt CO_{2e}] lower in 2030 (20). This is the emissions pattern during the last years and the projections for future:



Graph 2. Historical and projected decarbonation rate (20).

Achieving Australia's 2030 and 2050 targets means accelerate its decarbonisation rate to at least 17 [Mt CO_{2e}] per year, on average, for the next eight years to 2030 (data are from 2022).

Every Australian state and territory has committed to net zero emissions by at least 2050, with most supported by interim 2030 emissions reduction targets:

Jurisdiction	2030 emissions reduction target (per cent)	Baseline year	2020 emissions compared to 2005 levels (per cent)	2050
New South Wales	50	2005	-18.1	Policy target of net zero by 2050
Victoria	45–50	2005	-29.8	Legislated net zero by 2050
Queensland	30	2005	-19.3	Policy target of net zero by 2050
South Australia	50	2005	-31.1	Policy target of net zero by 2050
Western Australia	*No 2030 target* (80 per cent government target)	2020	+4.0	Policy target of net zero by 2050
Tasmania	Net zero emissions or lower by 2030	N/A	-127.8	Net zero emissions or lower by 2030
Northern Territory	*No 2030 target*	N/A	+36.2	Policy target of net zero by 2050
Australian Capital Territory	65–75	1990	-18.5	Legislated net zero by 2045

Table 1. Australian state and territory emissions targets and progress (20).

Setting targets is the right way to start, but with only seven years to go until 2030, it is crucial that states and territories produce the practical plans needed to achieve these targets. It could be possible in many cases to achieve these objectives by developing technologies that already exist. BZE (Beyond

Zero Emissions, it is an important Australian think tank internationally recognized) notes that the success of their plan for achieving the 81 per cent emissions reduction ambition depends on supporting factors including: investment and coordination, skilled people and reliable supply chains (20).

The main plan adopted by the Australian Government is the Australia's whole-of-economy **Long-Term Emissions Reduction Plan** sets out how Australia will achieve net zero emissions by 2050. The Plan is focused on 'the how', on practical action to convert ambition into achi evement, because a target without a plan is meaningless. The main pillars of the plan are:

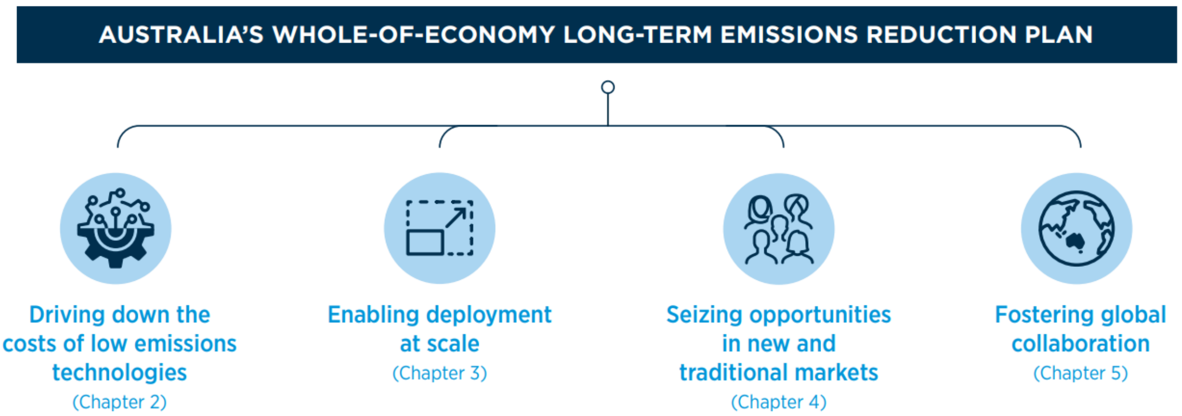


Figure 15. Main principles of the Australian's emissions reduction plan (21).

Affordable <u>low emissions technologies</u> are key to Australia achieving net zero emissions by 2050. The technologies prioritised through Australia's Technology Investment Roadmap (it is a document presents Australia's strategy to accelerate development and commercialisation of low emissions technologies) can deliver approximately half the emissions reductions needed to achieve net zero emissions (21). Currently the LETs and their target prices are:

Clean hydrogen	Clean hydrogen production under \$2 per kilogram
Ultra low-cost solar	Solar electricity generation at \$15 per MWh
Energy storage	Electricity from storage for firming under \$100 per MWh

Figure 16. LETs target prices (21).

Low emissions aluminium	Low emissions aluminium under \$2,200 per tonne (based on the marginal cost)
Carbon capture and storage	CO_2 compression, hub transport and storage for under \$20 per tonne of CO_2
Soil carbon	Soil organic carbon measurement under \$3 per hectare per year

Figure 17. LETs target prices ' (21).

Lived experience shows in many cases that there is an exponential relationship between falling technology costs and deployment at scale. By taking as an example the solar electricity production, research and deployment efforts started since the early 1970s, but it took until 2002 to deploy the first gigawatt [GW] of solar globally. Over the following decade (2002-12), 100 [GW] were deployed. By the end of 2022, more than 1000 [GW] of solar will have been deployed globally. Today, more than 90% of solar cells globally use Australian technology. Australia aims to replicate this success with the next generation of low emissions technologies. Australia is working not only to reduce technology costs, but also to remove barriers that may slow deployment across each economic sector. The Government is playing an enabling role to unlock investment and scale up technology deployment. This includes cross-cutting measures that apply across all sectors, and measures focused on overcoming barriers to technology deployment in individual sectors (21).

Australia's regions have always powered the growth of the nation and the Government will continue to support regions and traditional industries. In regional Australia live one third of the population and this number is destined to increase due to the increasing of new low emissions technologies and also the strengthening of traditional industries.

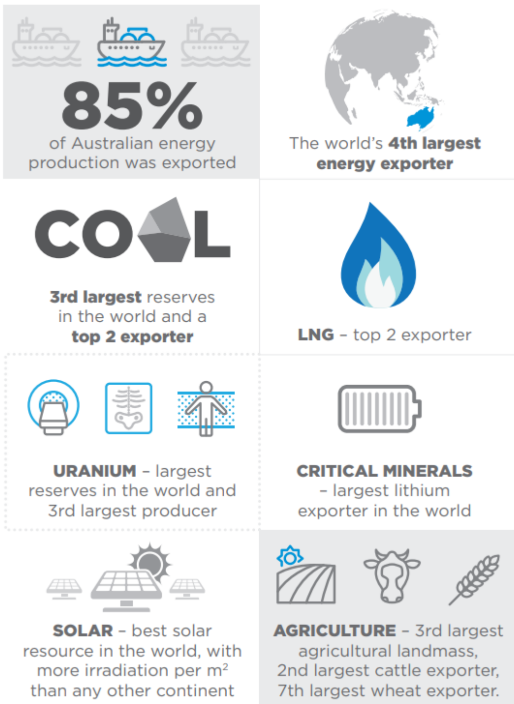


Figure 18. Australia's comparative advantages and natural endowments (21).

Changes in global demand for energy exports and the actions of the trading partners will have implications for Australia regional communities. The changes that will occur in the world due to the energy transition, can reduce work places in traditional industries. By building new industries like clean hydrogen, the plan will create new export markets and jobs. Australia will build on comparative advantages to grow new and existing export industries.

Australia is partnering and co-investing with other nations to accelerate the technology transformations needed to decarbonise the world's economy, not just its. Scaling up global production and supply chains will lower the costs of deploying the technologies all countries (including Australia) need. Australia is also working with other countries, especially within the Australia territory, so they can access and adopt new technologies and build resilience to climate impacts. They are also working with some neighbours in the Indo-Pacific to build a high-integrity carbon offsets scheme (21).

2.2.4) Australia's investments and institutions

In Australia there are mainly two organizations that invest in energy transition projects. Here we are going to analyse them and their investments but also a plan that is currently active in the country with the aim of increasing the share of renewable energy.

- The **Australian Renewable Energy Agency** (**ARENA**) was established on 1 July 2012 by the Australian Renewable Energy Act of 2011. Their purpose is to support improvements in the competitiveness of renewable energy and enabling technologies, increase the supply of renewable energy in Australia, and to facilitate the achievement of Australia's greenhouse gas emissions targets by providing financial assistance and sharing knowledge to accelerate innovation that benefits all Australians (22). Their funding is focused on finding and demonstrating technology solutions and business models that reduce technical, commercial and regulatory barriers and improve Australia's knowledge and expertise. These are the statistics for ARENA investments in the last decade:

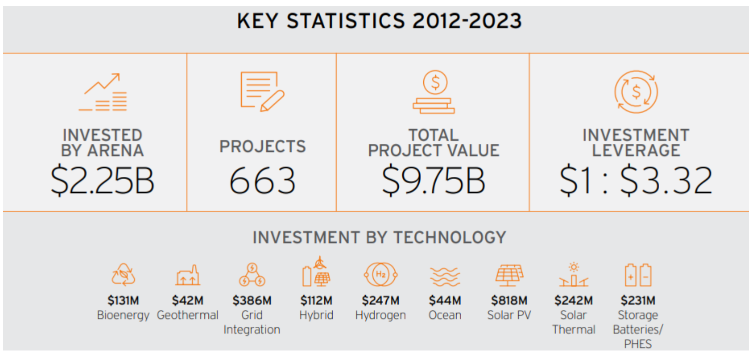


Figure 19. ARENA investments in the last decade (23).

- The **Clean Energy Finance Corporation (CEFC)** is a state-owned green bank that invests money related to clean energy projects. Up to now it has invested AUD 10 billion on behalf of the Australian Government. The CEFC invests in various sectors, including: renewable energy, energy efficiency, sustainable infrastructure, sustainable transport, clean and innovative technologies and agriculture and environmental sector. It collaborates with the private sector and other organizations to facilitate these investments and contribute to a cleaner and economically sustainable energy system. Specific investment areas and projects may vary over time based on market needs and opportunities. These are the main investments during the last year:

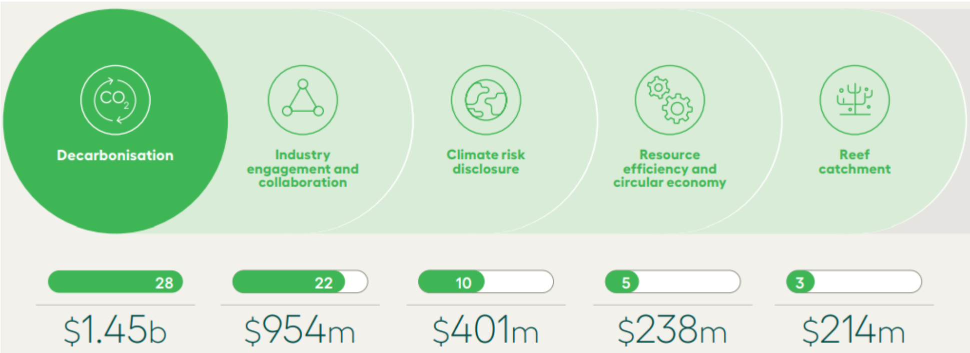


Figure 20. Assessment of new transactions completed in 2021–22 (24).

➢ Australia's **Renewable Energy Target (RET)** scheme encourages renewable electricity generation. It aims to reduce greenhouse gas emissions from the electricity sector. It consists in two main schemes, both are based on the emission of REC (Renewable Energy Certificates):

- The Large-scale Renewable Energy Target (LRET) requires high-energy users to acquire a fixed proportion of their electricity from renewable sources. This occurs in the form of large-scale generation certificates (LGCs), which are created by large renewable energy power stations (such as solar or wind farms) and then sold to high-energy users (mainly electricity retailers) who must surrender them to meet their obligations under the LRET. For example last year (2023) the fixed amount of energy from renewables was of 33000000 [MW].
- The Small-scale Renewable Energy Scheme (SRES) provides a financial incentive for individuals and businesses to install small-scale renewable energy systems such as rooftop solar, solar water heaters and heat pumps. This occurs in the form of small-scale technology certificates (STCs). They can receive a discount on their electricity bill or they can sell small-certificates to energy producers.

This system will be replaced by Australia's Guarantee of Origin which is a transparent, public and voluntary scheme that Australia's government is developing for consumers that can verify emissions claims about products, for promoting international trade of sustainable products and for producers that can better quantified the qualities of their outputs. In this scheme there are two certifications: Product GO (for products, that can be traded) and REGO (for renewable energy produced within Australia). The second one will substitute the actual certificates inside the RET from 2030 when the actual system will end.

Then there are also other incentives such as the **Emissions Reduction Fund** and the **Safeguard Crediting Mechanism**. The first provides businesses with the opportunity to earn Australian carbon credit units (ACCU) for every tonne of carbon dioxide equivalent a business stores or avoids emitting through adopting new practices and technologies. They can work also as a carbon offset if you have emitted more. The SCM allows businesses and facilities to earn credits if they keep their emissions below their established baselines. In other words, if a facility emits less than the allowable limit, it can earn emissions reduction credits. These credits can then be used to offset excess emissions at a later date or potentially sold in the carbon market. These methods are discussed in detail in the Carbon Pricing's chapter.

3) CARBON PRICING

Carbon pricing is one of the most important mechanism that nowadays is used as an ally against GHG emissions. It works by placing a fee on emissions or by distributing monetary rewards for those who emit less. In a long-term timescale it leads to a global emissions reduction and it encourage companies to reduce their impact by investing in low emissions technologies. The initial price of carbon (that usually is measured in CO_2 equivalent, a measurement unit that will discuss in the next chapter) is decided by measuring the costs of emitting carbon in terms of damage that it can produce – i.e. the costs related to extreme weather events as rainfalls, heat waves and droughts. They can measured by evaluating the damages to crop production, buildings, or directly on the population. Furthermore it take into account also the ice melting that leads to an increase in sea levels. Then with this method the responsibility for climate changes can be shifted from the public to the emitters. These last ones have the opportunity to choose, if they want to pay for their emissions and continue to pollute they can do so or if they want to invest money in reducing them, and the aim of carbon pricing methods is made this second option the less expensive. In this way, the overall environmental goal is achieved in the most flexible and least-cost way to society. As we said before, usually this structure encourages the developing of new low emissions technologies, new low impact fuels by trying to continue to grow economically. One important aspect where we are going to focus in the next chapters is carbon capture and storage (CCS), that could be a promising technology for companies that stored they emissions because a stored emission can be consider as not emitted and they can get tax credits for carbon offsets. Moreover there are also possibilities of using those captured emissions instead of storage them (in this case we are talking of Carbon Capture Storage and Utilization).

The two main Carbon Pricing mechanisms that are currently adopted are (25):

- **Carbon Tax**. A carbon tax method directly sets a price on carbon. It can do that in two different ways: by defining a tax rate on GHG emissions; based on the carbon content of the fossil fuel that the emitter is using. A carbon tax does not predetermine a quantitative emissions reduction for emitters, it just decide a price for them. Consequentially carbon intensive industries will start to develop new operative ways in order to pay less. This reflects in a quantitative emissions reduction.
- **Emission Trading System** (**ETS**). This system is more complex compared to the first one. It is characterised by the development of a market where emitters can trade emission units and it sets a quantitative limit on emissions. Each emitter has a baseline to respect, if it exceeds it

have to buy certificates if it is under the baseline it can sells certificates to others. This mechanism creates markets (that usually are virtual) thanks to the supply and demand for emission units. There are two main types of ETS mechanisms:

a. Cap and trade systems: It is the most common one, it applies a cap or absolute limit on the emissions. Then it is redistributed within the emitters. This cap is decided in function of big goals (i.e. the Europe cap is related to the goal of being under 1.5 [°C] of global warming). Firstly the emissions allowances are distributed to each emitter, usually for free but sometimes also through auctions. Then, at the end of every timestep based on their real emissions the involved entities can sell or buy allowances. Of course, in order to reduce emissions at every timestep the cap should decrease. This aspect will be discussed better especially in the Europe ETS system.

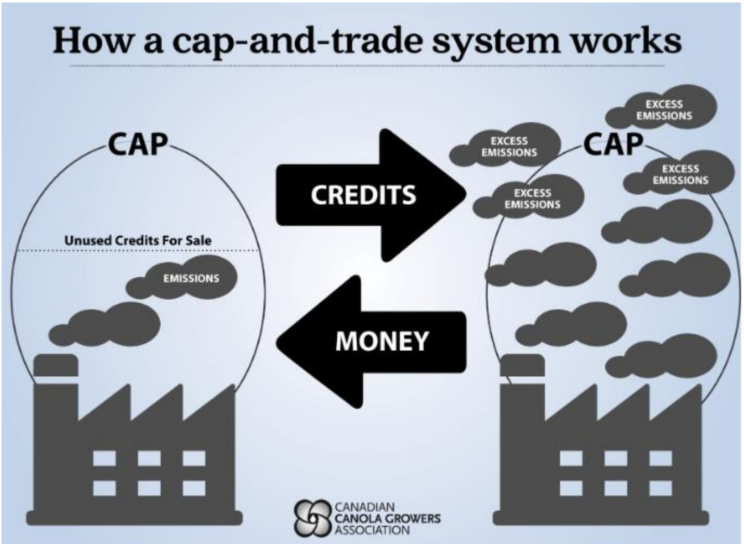


Figure 21. How cap and trade system works (26).

b. Baseline and credit systems: Here the main difference is the baseline calculation method. It is defined through the previous pattern of a certain emitter by trying to reduce it every timestep. The allowances distribution and exchange is similar to the previous system.

It could be possible when the authorities need it to consider also an **Hybrid Approach,** it can mix between them some characteristic from both systems. For example, a jurisdiction might set up an ETS with either a maximum or minimum price per allowance, or set up a carbon tax scheme that accepts emission reduction units to lower tax liability.

There could be some problems related to Carbon Pricing. The main one is related to global trade. If just few countries have a carbon pricing mechanism they could be disadvantaged because their emitters (so industries, electricity producers and so on) are less competitive in global market, having a part of their money to spend in emissions reduction or offset projects. This can be solved by applying fees on imported goods based on emissions content. In Europe there is this system and it works together with ETS (it is called CBAM). The current global situation luckily underlines that two-thirds of all submitted Nationally Determined Contributions (NDCs) under the Paris Agreement are using a carbon pricing mechanism to achieve their emission reduction targets. This means that around 100 countries firmly believe that carbon pricing is a way to achieve their NDC through international trading of emissions, offsetting mechanisms, carbon taxes, and other approaches (25).

What is the current Carbon Pricing status in the world?

- Currently there are 46 carbon pricing initiatives already active or planned for implementation, 23 are ETSs, applied both in single country but also to groups of countries, and 23 are carbon taxes, mainly implemented on the national level.

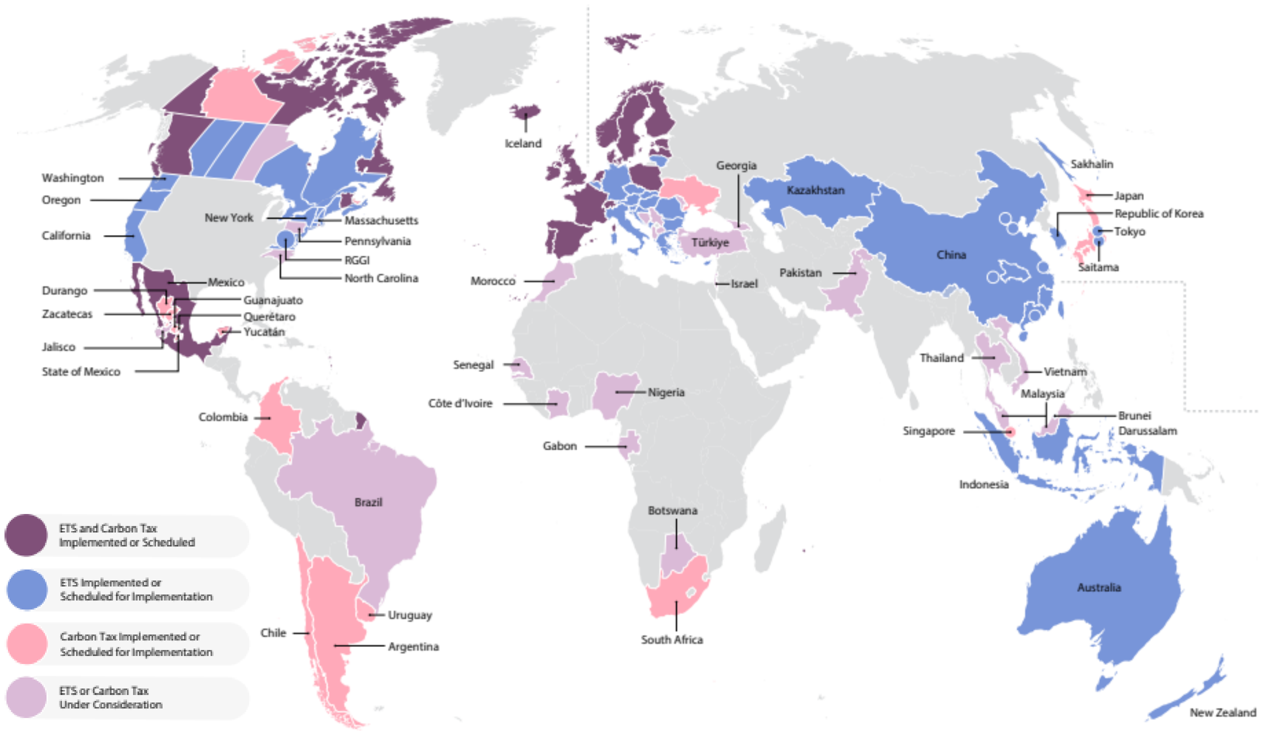
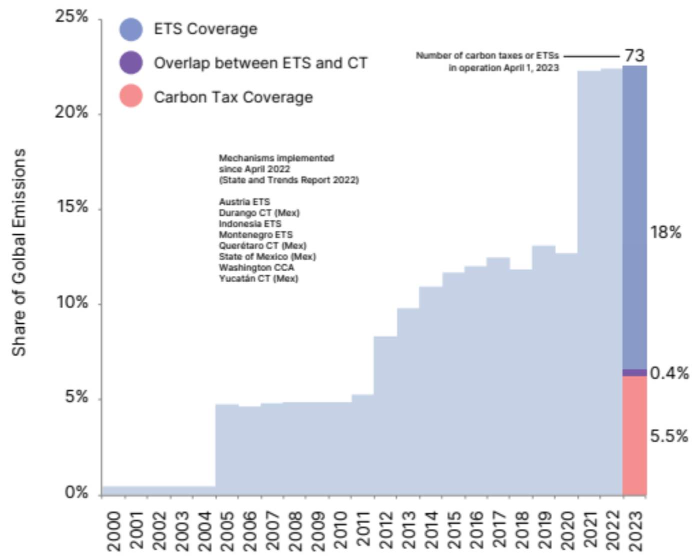


Figure 22. Summary of world carbon pricing (27).

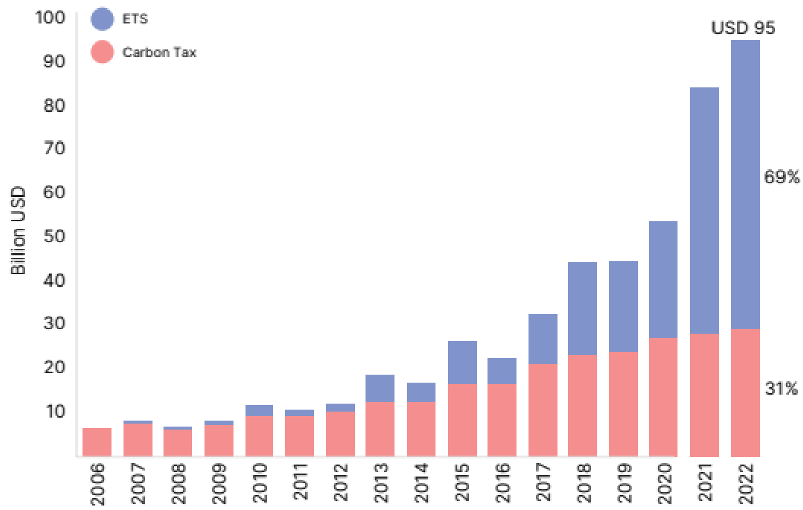
- ETSs and carbon taxes in operation cover around 24% of global GHG emissions (8,5 [billion tons] of CO_{2eq}.



Graph 3. Share of global emissions covered by ETSs and Carbon Taxes (27).

We can see from the graph that the highest percentage is covered by ETS systems around the world. This is due mainly to the Europe ETS system that is the biggest one, both for emissions quantities that for countries involved.

- The revenues generated from carbon pricing mechanism appear to grow year by year exponentially. In the last year (2022) there was an increase of 10 % in global revenues compared to the year before by reaching USD 95 billion globally:



Graph 4. Evolution of global revenues from Carbon Taxes and ETSs over time (27).

It could be possible to analyse the main differences between the two carbon pricing systems and then we can verify and underline them in the next paragraphs when we are going to talk about Europe and Australia carbon pricing mechanisms.

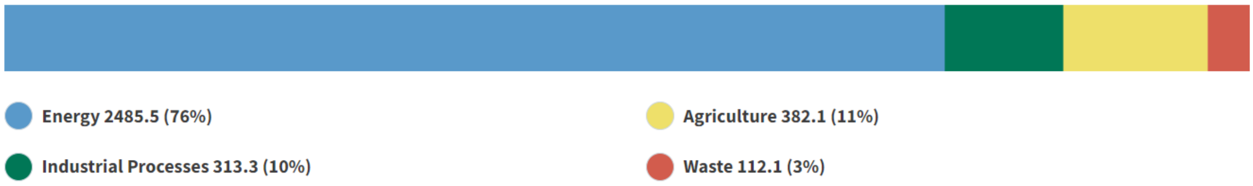
	ETS	Carbon Tax
Emissions threshold	The government can evaluate it and have precise forecasts for the future.	On average it reduces emissions but we do not have precise forecasts about emissions and the only way to verify them is when they are already emitted.
Price	It is not predetermined, it is based on market demand and supply, then it might be difficult for a company to develop specific economic plans.	The price is predetermined, the companies can plan and invest also in the long term.
Impact on hard to abate sectors	They are helped thanks to sector baselines and through the allocation of free allowances to them to prevent the carbon leakage phenomena.	It can drive to carbon leakage phenomena (movement in other countries for industries that are high carbon dependent e.g. steel and cement).
Administrative complexity	Difficult and hard to develop and implement, government have to decide the cap, its reduction through the years, create a system for allowances allocation and also a market.	Much easier compared to a trading system, it just puts a price on carbon emissions.
Revenues	It is possible for a company to gain. They can develop strategies of emissions reduction and sell their allowances thanks to the trading system.	The only entity that gains from this system is the government.

Table 2. Comparison between ETS and Carbon Tax systems.

3.1) European Union EU-ETS system

In Europe, even if there are some countries that have their internal regulations the main Carbon Pricing system is represented from the EU ETS. This is included in the Fit for 55 package (within the Green Deal) as one of the initiatives against climate changes.

Operational since 2005, the European Union Emissions Trading System (EU ETS) is the oldest carbon pricing system of the world. The system covers some 10,000 stationary installations, in the energy, industry sectors and recently it has involved also aviation.



Graph 5. GHG emissions covered by EU ETS by category in 2021 (28).

This represented around **38% of the EU's total emissions** in 2021. The greenhouse gases covered are: CO_2, N_2O and PFCs (Perfluorocarbons).

How does it work?

Before the start of each phase of the EU ETS, the EU sets an overall emissions reduction target for all member states. This target is decided from an international task force of scientists and it is based on the EU's GHG emission reduction commitments to respect mainly the Paris Agreement but also other environmental initiatives. The number of emission allowances corresponds to the difference between the target of the year before, and they will be allocated to EU countries. In phase 4 (where we are currently) 57 % of the allowances is distributed through auctions, the rest for free. The free allowances and the caps for each country are distributed to each state after the approval of their National Allocation Plan (each member country has to submit it) that decide the reduction of emissions in that state and the allowances deserved on the base of past emissions, future forecasts, economical and technology factors. The allocation within each country is based mainly on two factors: sectorial benchmark and carbon leakage. This sectorial benchmark is based on best available technologies on the market, then a more efficient company gets more EUAs (name of the European allowances) than one less efficient. The second factor is useful for preventing the movement of high carbon dependent industries outside Europe (steel, cement ecc), so they receive more allowances than the others.

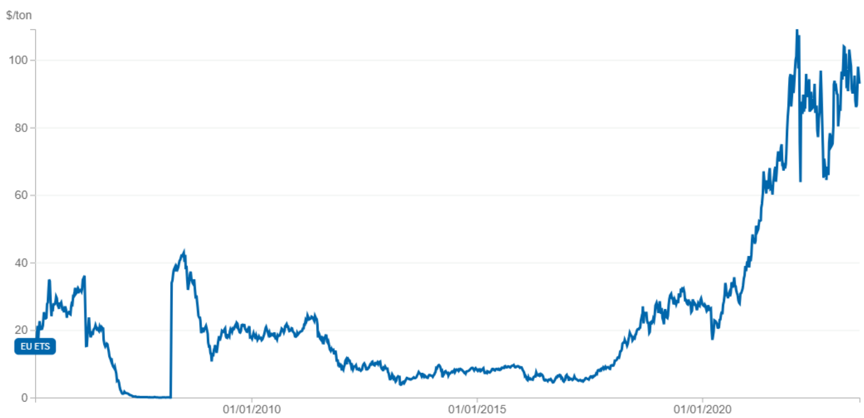
The facilities related to their GHG and their main greenhouse gas are (29):

- CO_2
  - Electricity and heat generation;
  - Energy-intensive industry sectors, including oil refineries, steel works, and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals;

- Aviation within the European Economic Area and departing flights to Switzerland and the United Kingdom;
- maritime transport;

- N_2O from production of nitric, adipic and glyoxylic acids and glyoxal;
- PFCs from the production of aluminium.

Facility operators involved in this system (then the ones that emit GHGs) once a year must present allowances for the emissions they produced. If they have emitted less than their cap it is possible to obtain a monetary revenue by selling this allowances on the market, otherwise if they exceeded it they must buy the allowances. The allowances are known as EUA and they represent a ton of equivalent carbon dioxide saved. EUAs can be sold or bought on markets where the price is based on supply and demand. EU emission allowances do not exist as documents - trading are in purely electronic form, similar to electricity trading. The most important trading venues are the ECX (European Climate Exchange) in London, the EEX in Leipzig and the EXAA in Vienna. The deadline for European countries is April 30 of each year, when plant operators must disclose their emissions allowance balance. Plants operators can decide the strategy to adopt every year. Based on the market price of EUAs they can invest in projects to reduce emissions (low emissions technologies, energy efficiency programs, change their energy mix and so on) or they can decide to continue to pay for them. This is the pattern of EU ETS price since its beginning in 2005 where its first price was around 20 USD $:



Graph 6. EU ETS value over years (28)

The drop near zero of CO_2 prices around 2007/2008 was for the economic crisis with the consequent drop of energy production. At that time the allocation of allowances was mainly for free and there were too many EUAs than the ones they really needed, so no one bought them on the market.

The Eu ETS system has had 4 phases: 2005/2007 – 2008/2012 – 2013/2020 – 2021/2030.

The **caps** for phase 1 and 2 were:

- Phase 1 started with a cap of 2,096 [$MtCO_{2e}$] in 2005;
- Phase 2 started with a cap of 2,049 [$MtCO_{2e}$] in 2008;
- As far as it concerns the phase 3 a single EU-wide cap set at 2,084 [$MtCO_{2e}$] in 2013, reduced annually by a linear reduction factor of 1.74% (of 2008-2012 baseline emissions). This means that every year the emissions reduction had been around 38 million allowances (tons of CO_{2e}) and resulted in a cap of 1,816 [$MtCO_{2e}$] in 2020;
- A single EU-wide cap of 1,572 [$MtCO_{2e}$] in 2021, subject to a linear reduction factor of 2.2% per year (of 2008-2012 baseline emissions). This means that every year the emissions reduction had been around 43 million allowances (tons of CO_{2e}). In this case there is not a limit on reduction factor and this will continue to decline beyond 2030.

Aviation had separate cap both for phase 3 and 4 (before it was not included).

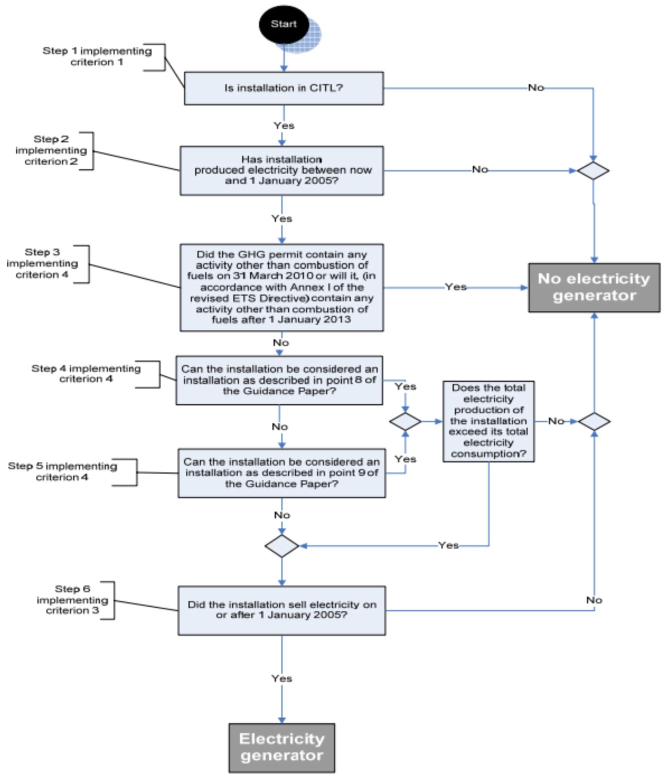
In the EU ETS, the main percentage of allowances revenues earn through auctions go to Member States' budgets. There is an obligation on spend this money for projects related to energy transition and fighting climate change. Member States must report annually to the European Commission on how they spent these revenues. The statistics said that on average, they spent 76% of their revenues in 2021 on domestic and international climate and energy related purposes (28). A share of allowances is auctioned (so they are not entirely distributed to facilities based on their baseline) to supply the Innovation and Modernisation Funds. These are two funds established for Phase 4 (2021-2030) to support decarbonization in the EU ETS sectors. What are they?

- **Innovation Fund**: The Innovation Fund is one of the most important funding programs for the demonstration of innovative low-carbon technologies. It develops industrial solutions to decarbonize Europe's energy intensive industries, and finances the development of renewable energy, energy storage, and also carbon capture use and storage.
- **Modernisation Funds**: Supports investments in ten lower income Member States (Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania and Slovakia) that in the vast majority of the cases have energy systems based on high emissions. It aims to modernise them by improving energy efficiency, and supporting a socially just transition to climate neutrality. It is one of the solidarity mechanisms of the EU ETS, that tries to give to

all member states the tools in order to do the energy transition and reach climate neutrality by starting from the same point.

3.1.1) Italy

Some countries in Europe have their own carbon taxes, as well as being under EU-ETS system. Italy does not have it, it is just under Europe pricing system, then, all the explanations made before are valid. Here the units included in the emission trading system are: boilers, burners, turbines, heaters, blast furnaces, incinerators, various furnaces, dryers, engines, fuel cells, chemical looping combustion units, flashlights and thermal or catalytic afterburners. As the directive says: "*included in the scope are plants that meet the threshold for the activity, namely: Installed thermal power of 20 [MW]; Production capacity depending on the activity carried out*" (30). Up to now, about 1200 Italian installations are involved, most of them are in the manufacturing sector (around 71%). Hospitals and "Small Emitters," i.e., installations with emissions of less than 25,000 [tons of CO_{2e}] and, in the case of combustion plants, with a thermal input of less than 35 [MW], without taking into account emissions from biomass, had the opportunity to be excluded from the EU ETS system with all the relative advantages (31). By the way, there is a specific guidance paper published in 2010 that allows to identify electricity generators:



Graph 7. Electricity generators identification (30).

In Italy the GSE (energy services manager) is part of the ETS Committee that is an inter-ministerial body with the function of the National Competent Authority for the management of the ETS Directive in Italy. The ETS Committee is also chaired by the Ministry of the Environment, Protection of Land and Sea (MATTM) while the Ministry of Economic Development (MiSE) is reserved for the vice presidency.

3.1.2) European Union future outlook: EU ETS-2

In July 2021, the European Commission proposed the "Fit for 55%" package of reforms that we already discussed in the Green Deal Chapter. One of the future policy contained in this package, is a proposal to extend ETS systems to new sectors that are not covered yet. In December 2022, the European Parliament and the Council of the EU agreed to establish a new ETS for emissions from: fuels used in buildings, road transport and certain industrial sectors not already covered by the existing EU ETS.

The agreement identify as a start year of this new system called ETS 2 the 2027 or 2028. The system will cover emissions upstream, therefore it will be related to fuel suppliers more than end-consumers. There will be an absolute cap on emissions and it will introduce a linear emissions reducing factor as the current ETS already has. The main difference is that EUA can be obtained just through auctions. The ETS 2 will be introduced together with a Social Climate Fund. Part of the revenues from auctions will be finance the fund that has the aim of supporting vulnerable households and micro-enterprises, with 25% co-financing from Member States.

3.2) Australia safeguard mechanism and carbon credit scheme

On the other hand in Australia there is a baseline and credit system called **Safeguard Mechanism**. It is a policy adopted from the Australia's government to reduce emissions in Australia's largest industrial facilities. The money invested from the government for this project are around $280 million in order to support industrial facilities to reduce their emissions (21). It works as an ETS system by setting limits known as baselines on the greenhouse gas emissions for each of these facilities. These baselines will decline, year after year, in line with Australian goals that we have illustrated in the second chapter (43% emissions reduction below 2005 levels by 2030 and net zero by 2050). The Safeguard Mechanism started in 2016 and it was reformed in the beginning 2023. The industrial facilities under this mechanism are the ones that emit more than 100,000 tonnes of CO_{2e} per year, including various sectors: mining; oil and gas production; manufacturing; transport; waste facilities.

In this ETS system the baselines are calculated for every facility based on its emissions previous pattern. As far as it concerns the electricity sector it is included in the mechanism but in a different way by applying a single ‘sectoral’ baseline across all electricity generators connected to one of Australia’s main electricity grids. The reforms will require large industrial facilities to play a significant role in Australia’s climate change fights, and they will help the country to meet its targets. To achieve this, it has been calculated that net emissions from all Safeguard facilities should not exceed 100 million tonnes of CO_{2e} at the end of first target goal (2029-30), 0 for the second goal 2049-50, and 1,233 million tonnes in total over the decade from 1 July 2020 to 30 June 2030. This means that over 200 million tonnes should be abated by the end of the decade. Also in the Australia’s system there are requirements for baseline decline, that started since 1 July 2023. The decline rate will be set at 4.9 % each year to 2030. Post-2030 decline rates would probably be set in five-year blocks. From the commencement of Safeguard Mechanism reforms in 2023-24, for all the facilities there will be adjusted baselines based on production, there will not be possible to have calculated and fixed baselines. For financial years ending before 1 July 2023, the Safeguard Mechanism required facilities to maintain emissions under the usual levels of that facility. For financial years commencing on or after 1 July 2023, the Safeguard Mechanism requires facilities to reduce their emissions in order to reach Australia’s climate targets. Safeguard facilities baselines will change in relation to annual production, but it will be also take into account a constant emissions decrease in order to respect Australia commitments (32).

Like in EU ETS system, Australia’s facilities obtain allowances called Safeguard Mechanism Credits (SMCs) when their emissions are below their baseline (there are dome exceptions for landfills and facilities accessing borrowing arrangements or deemed surrender provisions). After that facilities can sell this allowances to the ones that have emitted more than their baseline or they can also keep them for the following years. A market as the one that is currently used in Europe does not exist yet in Australia, but it is predictable that it will be formed in the coming years. This is how SMS system schematically works:

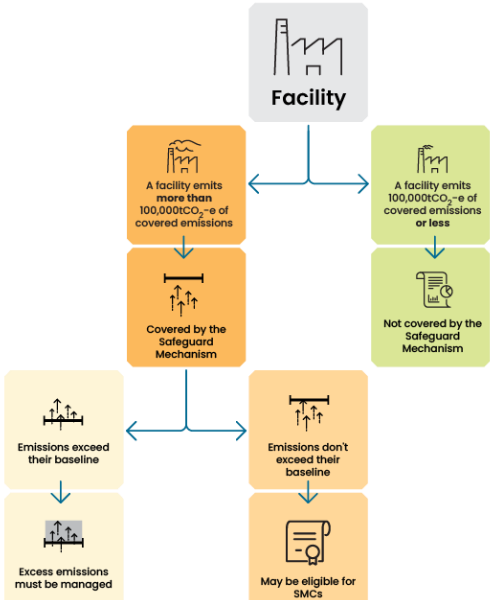
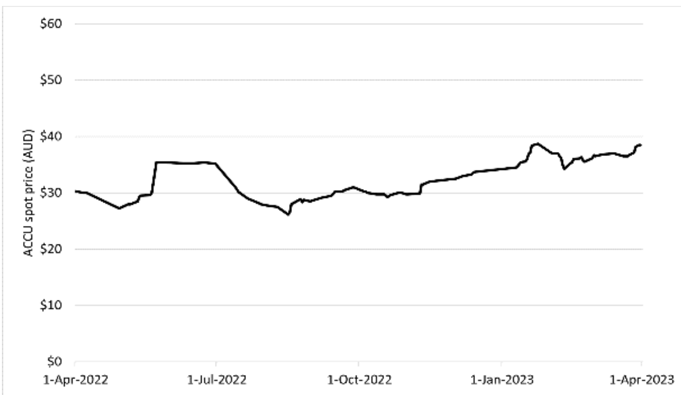


Figure 23. Safeguard Mechanism for financial years commencing on or after 1 July 2023 (32).

Currently the market of carbon is mainly based on an offset system in the country. Facilities can purchase and surrender domestic offsets in the form of **Australian Carbon Credit Units** (ACCUs) to meet their commitments. They already exited before the SMS mechanism started. An ACCU represents one tonne of emissions avoided or sequestered. How can they be obtained? Individuals, businesses, or organizations that start projects with the outcome of reducing or removing greenhouse gas emissions can register their projects with the Clean Energy Regulator (CER) in Australia. After the regulator has evaluated the project and verified that it meets its requirements the project financers can receive ACCUs in function of the quantitative of emissions avoided or removed thanks to their projects. The CER issues ACCUs to the project owners or operators for each tonne of CO_{2e} emissions reductions or removals achieved by the project. Currently ACCUs have a market where they can be sold and traded. These is the current pattern on the markets:



Graph 8. Generic Australian Carbon Credit Unit (ACCU) spot price (33).

Nevertheless SMCs are not offsets in the same way as ACCUs. SMS certificates are part of a bigger plan, where the certificates are emitted in relation to baselines based on Australia's climate goals that decline each year. Instead ACCU are just related to individual emissions abatement projects that are compared with the baseline of the single facility. Moreover it could be possible that a project that can gain ACCUs is not even included in the SMS system and vice versa. Although there are no limits on the use of ACCUs or SMCs, the availability of ACCUs and SMCs will be impacted by the anticipated scale of supply.

There will be the possibility for the facilities that will exceed their baselines to apply for a five-year multi-year monitoring program (up to 2030) when the firm has a credible plan to undertake an activity to reduce cumulative emissions before the end of the five-year period. This can helps facilities to be more flexible in their reduction plans while still respecting the constrains imposed by Australian climate goals. The Clean Energy Regulator administers the National Greenhouse and Energy Reporting scheme and the Safeguard Mechanism (34).

3.3) Carbon trading price influencing factors

As we already said in this chapter the initial carbon trading price is decided by measuring the costs of emitting carbon in terms of damage that it can produce. But how does it evolve over the time and which are the main influencing factors and how do they change it? Over the years there have been studies that tried to understand the correlations between the CTP and its main determinants especially for the European market (EU ETS system) but also for the Chinese one (there is an ETS system also in China). Thanks to these studies we are able to illustrate the main influencing factors (35); (36):

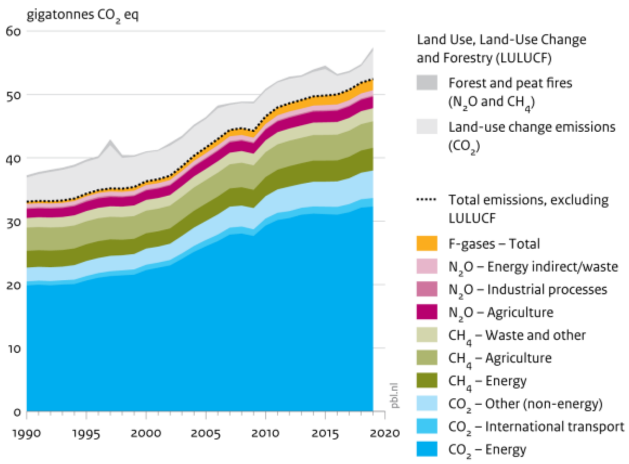
- **Macroeconomic factors**. Some mathematical models underlined the effect of the macroeconomic activities on CTP. The outcome was different. As an example in China a study analysed the pattern of CTP related to the GDP and it found an inversely proportional correlation, instead an ideal result would be the increase of CTP while GDP rises. On the other hand what was analysed in Europe is that during periods of economic growth the industrial production and consequentially emissions and energy demand increase and this is reflected in demand increasing for carbon allowances on the market with the final outcome of high CTP. Actually this is not always true because, especially in the last years both people, industries and governments during periods of economic growth tend to choose to invest in renewable energy generation and implement more restrictive environmental policies and this makes the previous considerations become incorrect.

- **Policy factors**. Of course government decisions and laws on emissions are a direct factor that influences carbon price and its pattern. The adoption of restrictive policies can increase the demand for emission credits and therefore increase carbon price if the total number of allowances that the government distributes has remained the same or if it has decreased. Moreover governments can provide economic incentives for low carbon emissions technologies to private people and industries with the outcome of the growth in CTP.
- **Environmental factors**. Here the opinions are discordant. Some scientists thinks that this factors have an impact on CTP other do not think so. Anyway some studies were conducted to find correlations between the air temperature and pollution to understand their relations with carbon price. A case study with United States as an example shows the proportional correlations between the air pollution and CTP in markets (positive) (37). Unfortunately it did not find analytical relations between air temperature and CTP, but anyway it underlined some mutual fluctuations. On the other hand a study conducted in China (38) revealed a negative correlation between CTP and air pollution, but it still did not find remarkable relations with air temperature. So, it is clear that there is an influence from this environmental factors but it is not properly understood yet.
- **Energy price factors**. The sectors more affected by these factors are the high carbon energy production (especially coal but also natural gas) and consumption (e.g. cement production and steel industry). When there is a CTP increase the cost of high carbon energy will grow. As a consequence the final clients will try to change their energy supply with a focus on renewables and low carbon content energies. So for sectors highly dependent on high carbon energies the profits will be reduced and especially for countries that rely a lot of their energy mix on fossil fuels there will be periods of economic drop because they will deal with the cheap prices offered in global markets by countries less dependent on fossil fuels. But this in the long term could drive the focus of countries and their industries on developments and investments in renewables sector and energy efficiency plans.

4) CARBON DIOXIDE (CO_2), COMPARISONS AND INDICATORS

4.1) CO_2 overview

Let is analyse the GHSs emissions patterns during the years. These are the global emissions trends (until 2018):



Graph 9. Global GHGs emissions trends (39).

We can see that the main GHG is represented by CO_2, and more than the half GHG emissions are caused for energy production. The unit of measurement in the graph is CO_{2e} that can be obtained from the concept of Global Warming Potential that compares every gas to CO_2. Each greenhouse gas lasts in the atmosphere for different lengths of time, and they also absorb different amounts of heat. The "global warming potential" (or "GWP") of a GHG indicates the amount of warming a gas causes over a given period of time (normally 100 years) compared to CO_2. The main greenhouse gases and theirs GWP are:

	Greenhouse Gas	Global Warming Potential (GWP)
1.	Carbon dioxide (CO_2)	1
2.	Methane (CH_4)	25
3.	Nitrous oxide(N_2O)	298
4.	Hydrofluorocarbons (HFCs)	124 – 14,800
5.	Perfluorocarbons (PFCs)	7,390 – 12,200
6.	Sulfur hexafluoride (SF_6)	22,800
7.	Nitrogen trifluoride (NF_3)[3]	17,200

Table 3. Main greenhouse gases (40).

But why have we choose carbon dioxide as a reference for greenhouse gas emissions even if its GWP is the lowest?

Firstly because CO_2 is the most emitted GHG into the atmosphere (about 80% of the total GHG emissions, as said by IPCC). As we can see from Graph 9 is by far the most produced by human activities. Consequently, the percentage of CO_2 in the atmosphere is the higher among GHGs. Furthermore, unlike others GHG, CO_2 persists in the atmosphere for long periods of time. Carbon Dioxide is a gas formed by two atoms of oxygen and one of carbon.

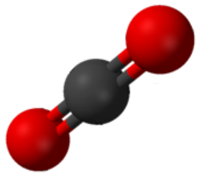
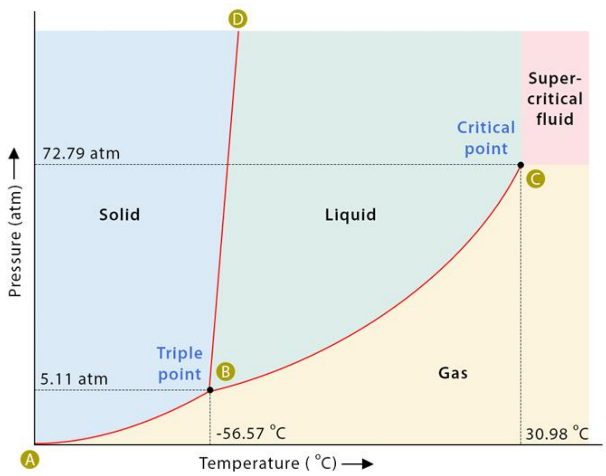


Figure 24. Carbon Dioxide (CO_2) (41).

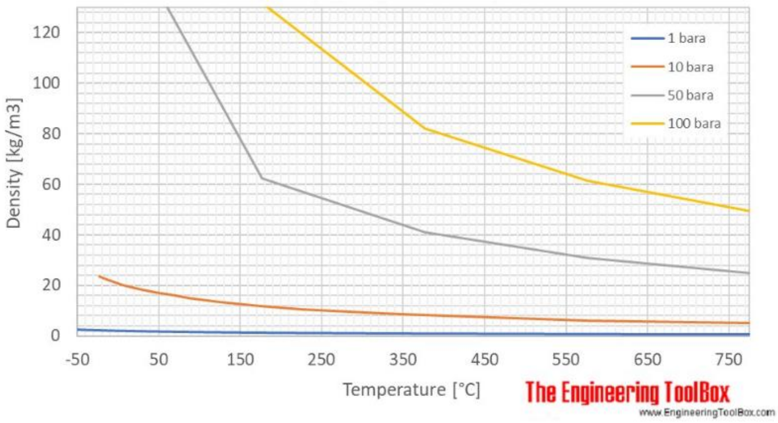
As we said before carbon dioxide it is essential for life on earth because it contributes to greenhouse effect. It is essential for many environmental, biological and geological cycles. It is an inert gas, non toxic under certain percentage and it is naturally produce from human body during respiration process while it is necessary for plants as inlet product for breathing. Carbon dioxide is considered toxic to humans at a concentration of 2.5 %, but since 0.08 % (800 ppm) concentration of carbon dioxide, performance, concentration and well-being are compromised (42). Therefore it could represent an hazard especially in close spaces with low ventilation.

This is its phase diagram, the one that underline the state of the substance as a function of temperature and pressure:

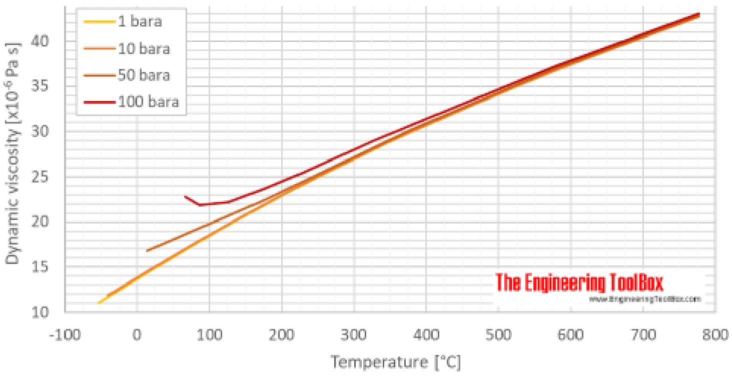


Graph 10. CO_2 phase diagram (43).

To fully understand the phase diagram of a substance we should explain the concepts of critical point and triple point. Above the critical point of a substance there is no change of state when pressure is increased or if heat is added (change in temperature). The triple point instead is where the three phases (gas, liquid, and solid) of that substance coexist in thermodynamic equilibrium. We can see from the graph that in the atmosphere CO_2 is in a gaseous state. For standard ambient conditions (25 [°C] and 1 [atm]) CO_2 has a density of 1,795 [kg/m^3] and dynamic viscosity of 14.93*10^{-6} [Pa s]. The diagrams below represent the pattern of density and viscosity with temperature and pressure:



Graph 11. Density of CO_2 at varying temperature and pressure (44).



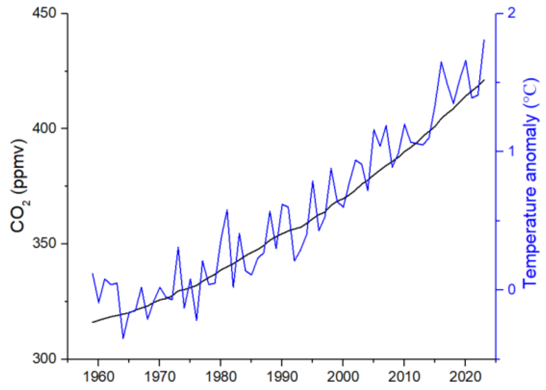
Graph 12. Dynamic viscosity of CO_2 at varying temperature and pressure (45).

Density and viscosity, as we can see from the graphs usually increase when temperature increases. This is always true for the density because if the temperature increases by maintaining constant the pressure, the density will decrease, in any state of our molecule. On the other hand, the viscosity rises with temperature just when CO_2 is in a supercritical or gas state, otherwise when it is a liquid it will decrease. But, due to the fact that our study aims mainly to analyse the CO_2 underground storage and it is impossible to find proper conditions for storing liquid CO_2 underground it would be useless to focus on the liquid state of this substance. In fact, if we focus on CO_2 underground storage, after having analysed its properties we can understand why it is stored as a supercritical fluid. The geothermal gradient of the earth is between 25/30 [°C/km] on average (it can be also bigger in geothermal active areas). The pressure gradient can be considered around 0,15 [bar/m] (the minimum values found in literature are around 0.02 [bar/m]) (46). If we consider a suitable storage site around 1000 [m] deep it will have an average pressure and temperature respectively of around 150 [bar] and 40 [°C]. This average thermodynamic state identified is located in the supercritical zone, this is the reason why CO_2 is stored in these conditions. In the vast majority of the cases supercritical conditions for CO_2 are found below 800 [m].

Power generation but also cement production and buildings consumption of fossil fuels have resulted in the emission of significant amounts of CO_2 to the atmosphere over the past decades. The end of the last century had faced a high increase in CO_2 emissions that had been increased by over 70% from 1970 to 2002. Due to the fact that in that period the carbon dioxide measurements were already started the scientists started to have a lot of concerns about the situation. Researchers have identified that between 1970 and 2002, global emission of CO_2 increased by over 70%. According to a study reported by Schubert and Jahren (47), the natural sources of CO_2 emissions (e.g., decomposition, ocean release, and respiration) are greater than the ones from human activities such as the burning of oil, coal, and gas; deforestation; industrial manufacturing; and the use of aerosols. However, the natural sources of CO_2 are closely balanced by naturally occurring phenomena such as photosynthesis and weathering of rocks. This naturally balanced process has made the atmospheric concentration of CO_2 to remain between 260–280 [ppmv] for 10,000 years before the start of the industrial era (48).

Nowadays the situation is completely different from the past. Orbital Forcing phenomena (discovered by Milankovitch), that probably have been driven the temperature in the past for long time scale, cannot account for the current period of rapid warming Earth has experienced since the pre-Industrial period (the period between 1850 and 1900), and particularly since the mid-20th century. Finally, Earth is currently in an interglacial period (a period of milder climate between Ice Ages). If there were no human influences on climate, scientists say Earth's current orbital positions within the Milankovitch cycles predict our planet should be cooling, not warming, continuing a long-term cooling trend that began 6,000 years ago (49). Today, an extensive network of international air sampling sites is operated by the National Oceanic and Atmospheric Administration's Global Monitoring Division (NOAA/GMD) in the USA. This organization has measured carbon dioxide and other greenhouse gases for several decades at a globally distributed network of air sampling sites. It is possible to use their data to analyse the patterns of the last few years. More precisely the measured data about CO_2

concentration start from 1959. The planet's average surface temperature has risen about 1 degrees Celsius since the late 19th century and the pattern is linear with CO_2 increase. Most of the warming occurred in the past 40 years, with the seven most recent years being the warmest. The current warming trend is different because it is proceeding at a rate not seen over many recent millennia then it is clearly the result of human activities since the mid-1800s. It is undeniable that human activities have produced the atmospheric gases that have trapped more of the Sun's energy in the Earth system. This extra energy has warmed the atmosphere, ocean, and land, and widespread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere have occurred.



Graph 13. CO_2 concentration and surface temperature anomaly 1959-2022 (50); (51).

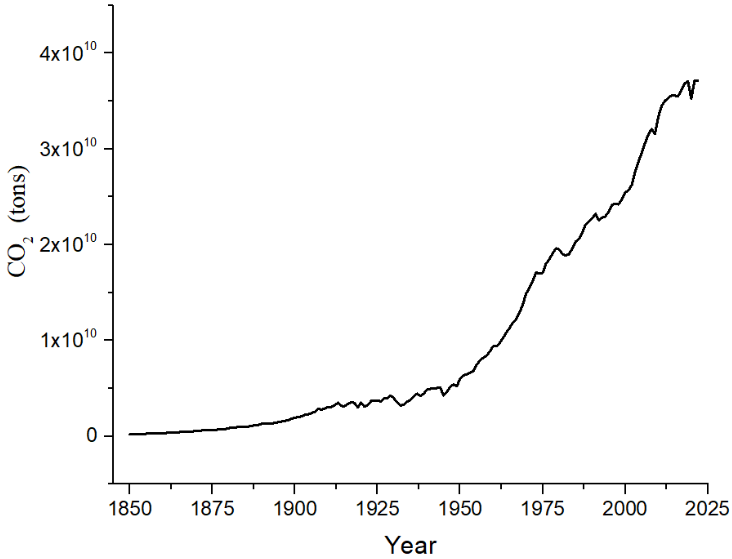
The values are annual based. It is evident that there is an increase in the average surface temperature due to the rise in CO_2 concentration. And we can also noticed how bigger is the concentration of CO_2 if compared to the one of the study reported above that says that the average before industry revolution was 270 [ppmv], in 2023 we had an average value of **421,08 [ppmv]**.

Where is this CO_2 mostly coming from?

Electricity and heat generation	35.8%
Manufacturing industries	16.7%
Road transport	15.9%
Buildings (houses, offices, etc.)	8.7%
Other national fuel combustion	7.9%
International transport (by air & water)	3.6%
Total fossil-fuel combustion	**88.6%**
of which:	
- coal combustion	43.8%
- oil combustion	34.6%
- natural gas combustion	21.6%
Non-energy use of fuels	4.4%
Cement clinker production	4.0%
Other carbonate use	1.2%
Carbon losses in coke ovens etc.	1.1%
Associated gas flaring	0.8%
Total other CO_2 sources	**11.4%**

Table 4. CO_2 sources (52).

We can see the emissions are mainly fossil-fuel based and the majority comes from electricity, heat generation, manufacturing industries and road transport. What is the current situation in terms of CO_2 emissions country by country and how has it change over the time? We can start the analysis from the total CO_2 emissions over the time, since 1850:



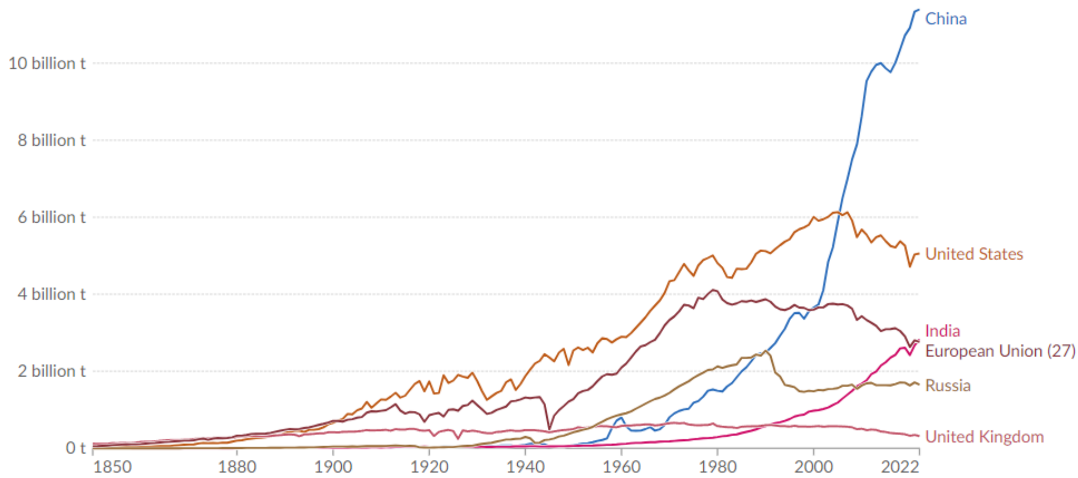
Graph 14. CO_2 emissions from fossil fuels and industry over the time (53)

We can see that since the beginning of the industrial era there has been an increase in the emissions. The graph underlines also the drop during covid-19, followed though by a fast growth the following year (2021). The peak in 2022 of **37,15 [billion tons]** of CO_2.

4.2) Comparisons and indicators

But, whose fault is it? Of the country that has emitted most during its lifetime or the one that is currently emitting most? We cannot forget that this gas remains in the atmosphere for a long time and the evolution of countries happens during different periods. We can analyse the problem from different points of view with different indexes:

CO_2 EMISSIONS PATTERN



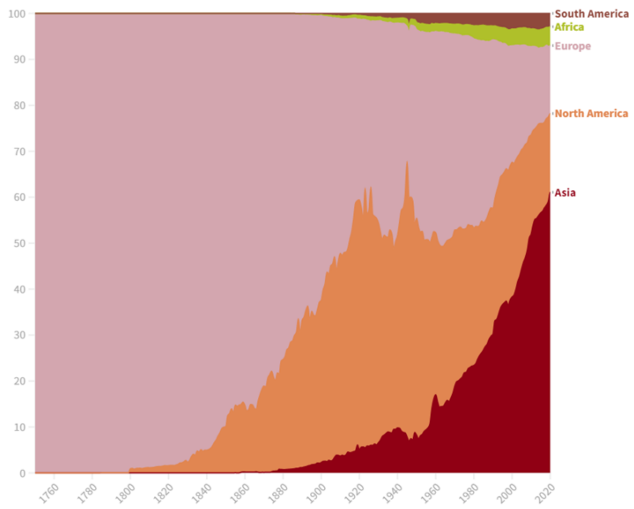
Graph 15. CO_2 emissions since 1850 (53).

If we zoom the graph it is noticeable that at the end of the first industrial revolution the first emitter country was United Kingdom, and there were not even China and India, while US emitted about one-fifth of the UK.

Then, in the middle of the 20th century the United States were the first emitter, we can also see a the beginning of growth in Russian's emissions, started around 1940. Moreover, from those years there was a trend of general increase in emissions in all the main countries until the beginning of the new century, except for UK that remained constant with a slightly decrease in the last decades.

Around the beginning of the new century we see decreases for the US, European Union countries and Russia (the last one with a huge drop after the end of Soviet Union). Simultaneously China and India had a huge rise.

Nowadays the main emitter is China, with a rapid growth in the last 20 years. Then in the fourth position there is India, that has followed a pattern similar to the Chinese one over the last years.



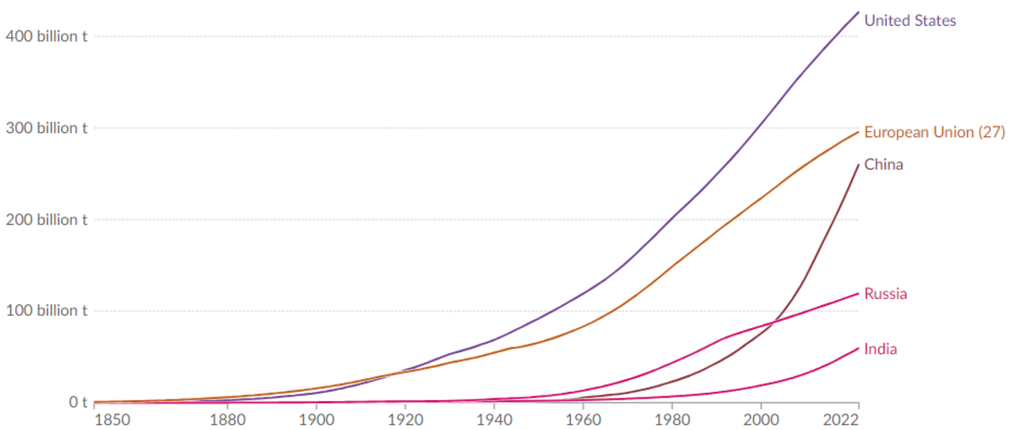
Graph 16. CO_2 by country over the time (3) (53).

From this last graph we can underline the main differences over the time, analysing the patterns of each continent. There are no doubts that nowadays the country that emits more is China and if we consider that in Asia there is also India, another country within the first four, it represents the main emitter continent of in the world. This is the ranking (2022):

1. China – 11,40 [Bt]
2. United States – 5,06 [Bt]
3. India – 2,83 [Bt]
4. European Union – 2,76 [Bt]

But, if we take into account the fact that CO_2 is a gas that remain into the atmosphere for a long time, who is the country that has emitted more during is lifetime?

CO_2 CUMULATIVE EMISSIONS



Graph 17. CO_2 cumulative emissions (53).

We discover that up to now the United States are the country that has emitted more CO_2 (more than 400 billion of tons), they are followed by European Union and China. Then, we can see the huge rise of China in the last years. Instead India has a cumulative emissions lower than UK, Germany and Russia too, but it has marked an increase since the beginning of this century. In numbers until 2022:

1. United States - 426,91 [Bt]
2. European Union – 295,97 [Bt]
3. China – 260,62 [Bt]
4. Russia– 119,29 [Bt]

CO_2 EMISSIONS PER CAPITA

Moreover, it is possible to evaluate the inequality between rich and poor countries related to CO_2 emissions. To do so, we must calculate the contribution of the average citizen of each country by dividing its total emissions by its population. This figure cannot be exhaustive because it only takes into account emissions produced within a country's borders, it does not take into account how goods are traded, but it helps to get a clear idea of the situation.

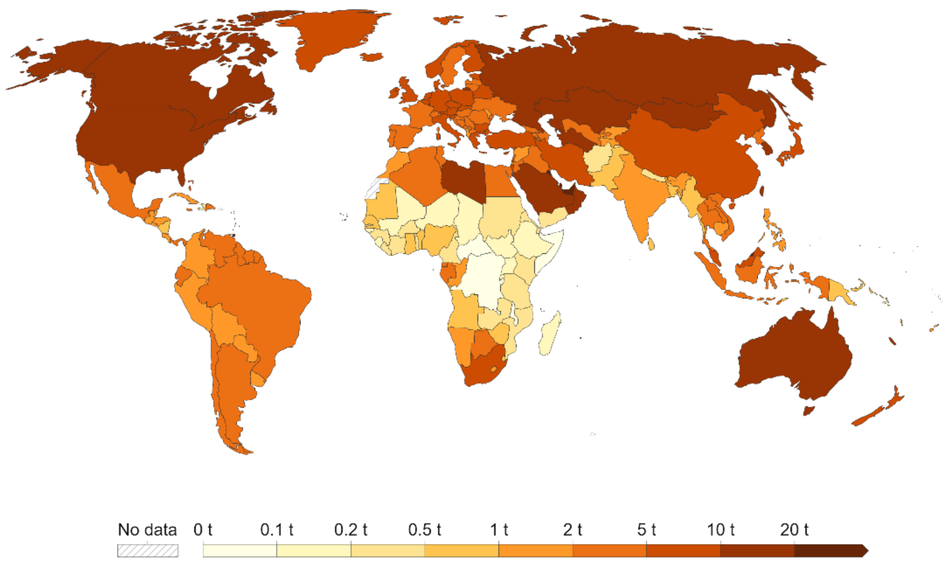


Figure 25. CO_2 emissions per capita (53).

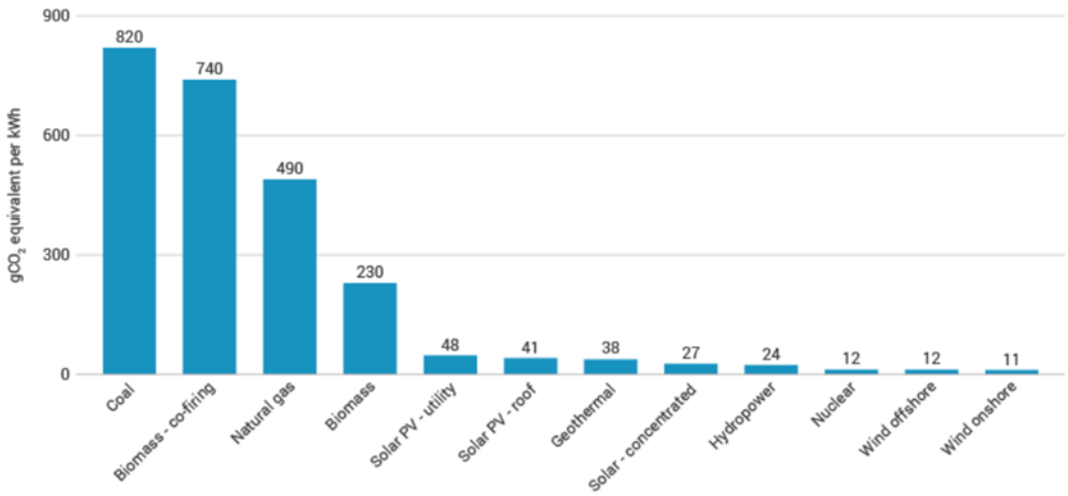
The largest emitters of CO_2 per capita in the world are the major oil-producing countries, and most are in the Middle East (Qatar, Kuwait, UAE, Brunei, Trinidad and Tobago, Bahrin and Saudi Arabia). However all of these countries have a small population, therefore their emissions are low overall. If we consider only big countries we find:

1. Australia – 15,1 [tons per capita]
2. United States – 14,9 [tons per capita]
3. Canada – 14,3 [tons per capita]
4. Kazakhstan – 14 [tons per capita]

We would expect that a country with high income has high emissions too. Actually this is not always true. It is function of many factors such as the energy mix used, kinds of transportation, technological advancement and so on. It is for this reason that for example European Union it is not in the first position, even if it is a country with living standards higher than other countries that are above it in the ranking. Among all the factors, the predominant one is the energy mix, that in the case of an high percentage of nuclear and renewable energies will reduce the emissions of that country.

CO_2 EMITTED FOR EVERY kWh

Finally, we know the average equivalent CO_2 emissions for every technology used to produce energy. Therefore we are able to estimate for every country, based on its energy mix, the average amount of CO_2 emitted for every kWh of energy produced. In particular, we did it for Europe, Italy and Australia. This are the emissions for the main technologies that produce energy:



Graph 18. CO_2 emissions based on technology used (54).

In Italy the energy mix for the last year (2022) declared from GSE (energy services manager in Italy) was:

Fonti primarie utilizzate	Anno 2022 %
- Fonti rinnovabili	36,84%
- Carbone	9,43%
- Gas Naturale	46,92%
- Prodotti petroliferi	2,01%
- Nucleare	0%
- Altre fonti	4,80%

Table 5. Italian energy mix 2022 (55).

So if we do a weighted averaged for Italy the energy production generates 450 [gCO_2/kWh]. This value is highly influenced by the massive energy production from natural gas.

Instead for Europe the energy mix is:

Fossil fuels in detail:

- Gas:19.6%
- Coal: 15.8%
- Oil: 1.6%
- Other: 1.7%

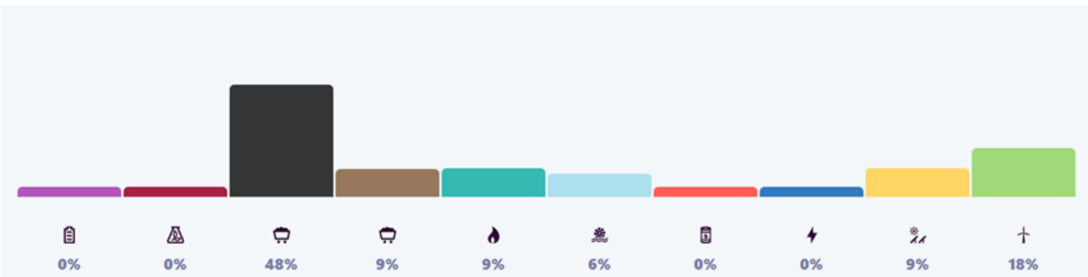
Renewables in detail:

- Wind: 15.9%
- Hydro: 11.3%
- Solar: 7.6%
- Biomass: 4.4%
- Geothermal:0.2%

Table 6. European energy mix (56).

The table does not consider the energy from nuclear that in Europe is 21,9%. Now we are able to evaluate the index also for Europe, and it is around 260 [gCO_2/kWh]. This means that if we consider Europe it is cleaner that just Italy in energy production. This low value for Europe is thanks to renewables and nuclear energy share.

As far as it concerns Australia this is its energy mix from AEMO (Australia Energy Market Operator):



Graph 19. Australian energy mix (57).

The weighted average for Australia is 500 [gCO_2/kWh]. So among these countries Australia is the one with the worst energy mix in terms of carbon dioxide emissions, this is due to the high share represented by coal.

Now that we know the average emissions for energy production and the cost of excess CO_2 produced it is possible to calculate another index. This one represents the cost that an energy producer pays for every kWh of electricity that it produces after it exceeds the threshold.

COST OF CO_2 EMISSIONS PER kWh:

In Italy the average emissions are 450 [gCO_2/kWh]. The cost that a company has to pay for excess CO_2 produced is related to the price of EUAs in the market. Currently it is around 90 [€/tonCO_2].

$$\frac{100\ x\ 90}{1000\ x\ 1000}x\ 450 = 4{,}05\ [\frac{c€}{kWh}]$$

This means that an energy producer in Italy pays 4,05 cents for every [kWh] produced that exceeds the emissions threshold.

As far as it concerns Australia the average emissions are 500 [gCO_2/kWh]. Currently a company that exceeds the threshold pays for an ACCU 38 [AUS$/kWh].

$$\frac{100\ x\ 38}{1000\ x\ 1000}x\ 500 = 1{,}90\ [\frac{cAUS\$}{kWh}]$$

It is obvious that the penalty for European countries is bigger just from the allowances price but with these data we can make a comparison with the price of energy in these two countries. In Italy the medium price of the energy is around 15 [c€/kWh] in the last year (58). Instead, in Australia, the cost of energy is around 28 [cAUS$/kWh] (59). Then the penalty applied in Italy weights is around a quarter of the energy price, much more than the Australia's penalty that is around 1/14 of the energy price.

4.2.1) Incentives for renewables and decarbonised

A last comparison can be done for incentives for a renewable product and decarbonised one. For example, we can analyse the hydrogen case.

The green hydrogen is the one produced from renewable energy mainly through electrolysis. To produce 1 kg of green H_2 we need between 50 and 65 [kWh] of energy (60). If we use 55 [kWh] as reference for 500 [kg] we need 27500 [kWh], let is hypothesize that it is completely renewable. In

Italy the main incentive for renewable production are green certificates. These can be traded from renewable plants to fossil fuel producers because a specific amount of energy has to be from renewables. The average cost of them in 2022 was 298,05 [€/MWh] (61). Then a renewable plant can sell the amount of energy it will use to produce 500 [kg] of green hydrogen for around 8200 €.

On the other hand we have the blue hydrogen. This is produced with the steam reforming method (from methane, so it is based on fossil fuel consumption) but the CO_2 produced is then stored. The amount of carbon dioxide stored is considered as not emitted therefore the company can receive a certain amount of EUAs. This is the steam reforming chemical formula:

$$CH_4 + H_2O \Rightarrow CO_2 + 4H_2$$

Then ideally I have 2 grams of H_2 every 11 g of CO_2. If my hydrogen is blue it means that during his production I stored the CO_2 produced. Actually it is quite impossible to store all of it, generally the one we can store is between 75 and 90% of the total. Then we can consider around 9 [g] of CO_2 every 2 [g] of H_2 (82%). Thus for the production of 500 [kg] of H_2 we stored 2250 [kg] of CO_2 and we lost 500 [kg] of CO_2 in the atmosphere. Let is hypothesize that we earned the money for the stored CO_2 because it is considered as not emitted, the price of EUA is now around 85€ for each tonne of CO_2, but I have also have to pay for the one I emitted. So it is (2250-500)/1000*85€ = 148,75€ earned for that stored CO_2.

Then from this comparison we can say that if we take into account just the incentives (and do not consider the costs of the plants) they are much higher for renewables than for decarbonised.

5) CARBON CAPTURE AND STORAGE (CCS)

In this world scenario Carbon Capture and Storage (CCS) or carbon capture, utilization, and storage (CCUS) is recognized internationally as an indispensable key technology for mitigating climate change and protecting the human living environment. Both the International Energy Agency (IEA) and the Carbon Sequestration Leadership Forum (CSLF) have stated that, in order for the energy sector to achieve net zero emissions by 2050, the global scale of CCS in 2030 and 2050 must respectively be 10–15 times and 100 times greater than the current 40 [Mt/a] (2020 data). The Intergovernmental Panel on Climate Change (IPCC) has projected that the cost of mitigation will rise by 138% in 2100 if CCS technologies are not adopted (62). While on one side CO_2 emissions from fuel combustion have been declining, industries like cement, iron and steel, aluminium, pulp and paper, and refineries have still high CO_2 emissions due to energy-intensive industry processes and actually there are still uncertainties about the transition of these industries. Carbon capture, use and storage can provide a key contribution to deal with the emissions in these sectors. But, what CCUS is and why is it useful to invest on it?

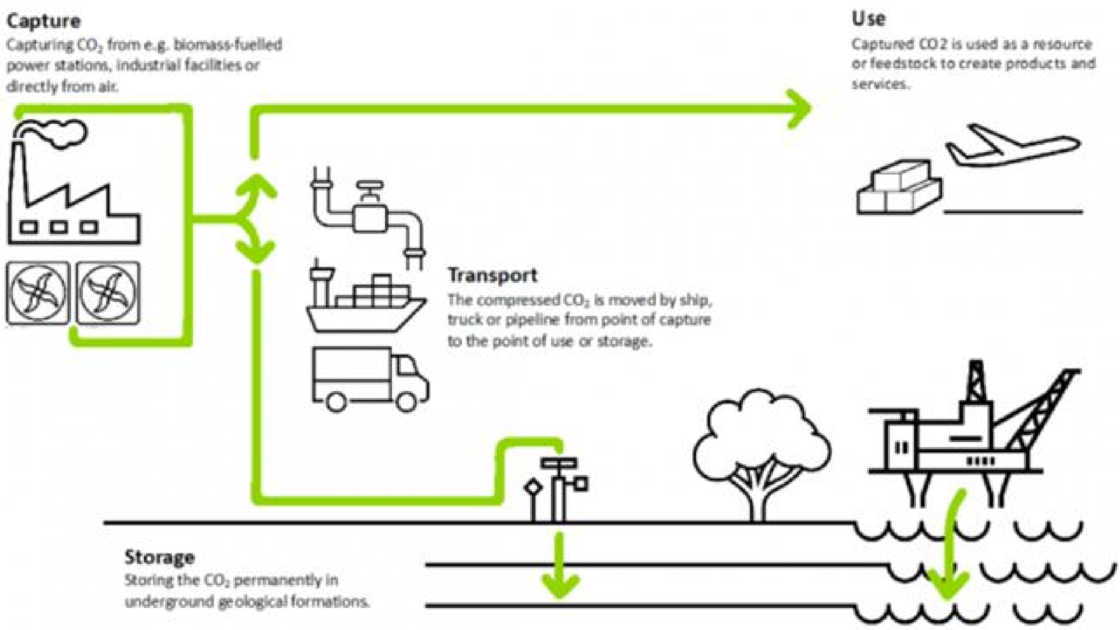


Figure 26. How CCSU works (63).

CCUS is a process that starts from CO_2 capture. Usually it is captured from point sources (power plants and industrial facilities). After that this carbon dioxide can be used, on site or after transportation. The main utilization for CO_2 are: soft drinks, using it as a working fluid or solvent, using it as a feedstock and converting it into value-added products such as polymers, building materials, chemicals and synthetic fuels. The transportation of CO_2 is mainly done by using pipelines but it is possible to transport it also through ships, trucks and trains (after it is compressed in tanks). For storing it, it is injected into deep geological formations such as depleted oil and gas reservoirs or saline aquifers that can be on or off shore. Currently there are studies related also to Direct Air Capture (DAC) technologies that extract CO_2 directly from the atmosphere at any location unlike carbon capture which is generally carried out at the point of emissions (DAC plants currently operate on a small scale, but with plans to grow) (64).

Currently the European Union is financing CCSU projects through some funds we already talked about as: the Innovation Fund, the Just Transition Fund and Horizon Europe. Furthermore, undertake such projects could be useful also on the economical side because of the carbon pricing systems active in the countries. In Europe an emission captured, transported and stored according to ETS directive will be considered as not emitted. The main European Directive related to CCS is the Directive 2009/31/EC on the geological storage of CO_2. It covers all CO_2 storage in geological formations in the EU and the entire lifetime of storage sites. It also contains provisions on the capture and transport components of CCS, though these activities are covered mainly by existing EU environmental legislation. It applies to commercial scale facilities with a capacity of 100 kilotonnes per year [$ktCO_2$/yr] or more. The European Commission works to ensure the coherent implementation of the CCS Directive in all Europe. These include reporting on the implementation, facilitating exchanges between the competent authorities, publishing guidance documents, and adopting commission opinions on draft storage permits.

Overseas in Australia there is the development of 2050 Net Zero plan. The Department of Climate Change, Energy, the Environmental and Water mentioned CCSU technologies as an essential part of this plan in order to reach its goals. It says that "*Along with other technologies, CCUS and negative emissions technologies may help reduce and remove emissions for some industries. Examples include cement manufacturing, production of fertilisers or industrial chemicals*" (65). Australia have many laws and regulation about offshore CCS projects. Also in this country a project gains allowances (in this case they are ACCUs) if it emits under a baseline. This means that a CCS project that reduces the CO_2 emissions in the atmosphere will obtain certificates as those emission would have never been emitted. On the other hand the onshore projects are under the jurisdiction of single states. Currently the Carbon Capture Technologies Program grants of up to 15$ billion to support the research and development of new ways to capture and use carbon dioxide, especially in hard to abate sectors such as cement manufacturing. Also Powering the Regions Fund (PRF) grant programs could support

CCUS projects where they are proposed by eligible entities and meet the merit criteria. This is a fund that support the decarbonisation of existing industries and creation of new clean energy industries through $1.9 billion.

CAPTURE

This work is mainly focused on carbon storage, but in order to have an overview of the topic we are going to briefly analyse also the capture and transport methods. There are three basic systems for capturing CO_2 from use of fossil fuels and/or biomass and one new promising method:

1) Pre-combustion capture
2) Post-combustion capture
3) Oxy-fuel combustion capture (during combustion)
4) Direct Air Capture

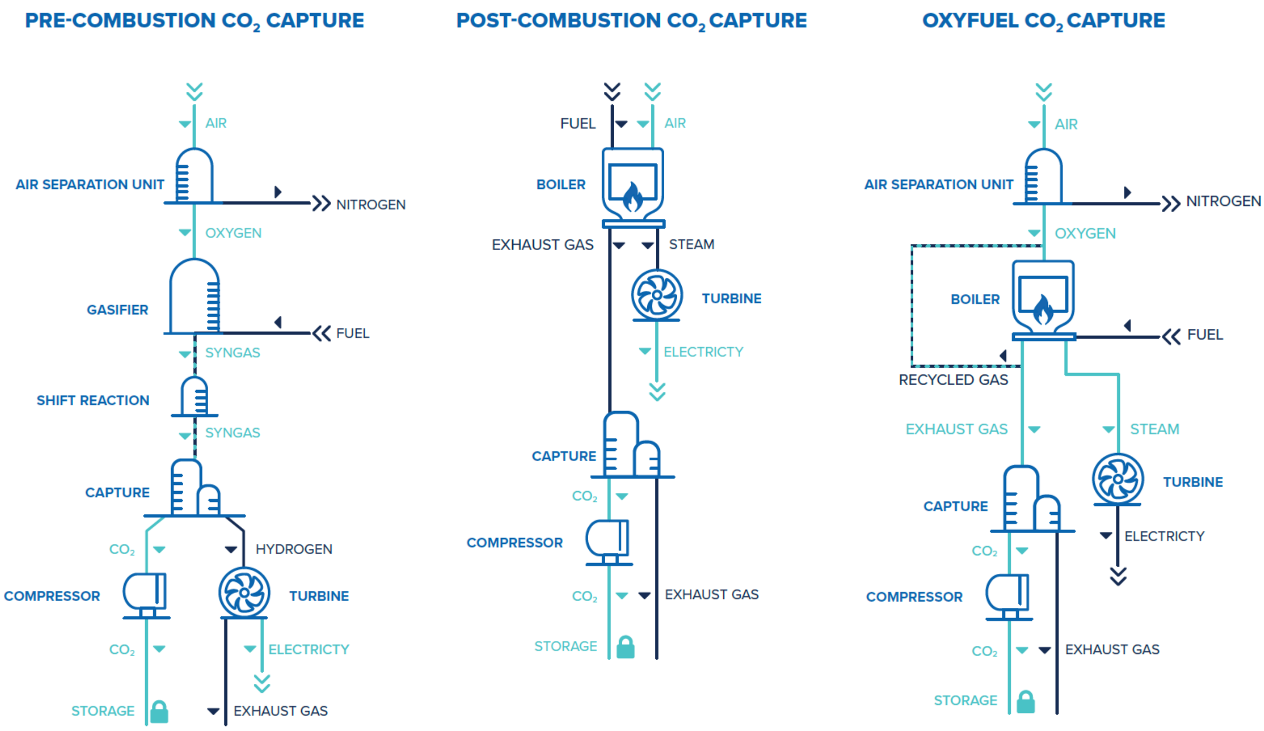


Figure 27. Carbon Capture methods (66).

Pre-Combustion Capture

In this method firstly nitrogen is removed from the air. After that the fuel (coal, gas, biomass) is converted into a mixture of CO and H_2 (syngas) in the reforming or gasification process. Subsequently, using the water–gas shift, CO_2 and H_2 are produced. Carbon dioxide is then captured while hydrogen may be used as a fuel for a turbine. Pre-combustion carbon capture uses physical and chemical methods to capture CO_2 from processed syngas. The capture efficiency achieved from this method could be pretty high, more than 90%, but unfortunately this reduces the efficiency of the plant. (67). Even if the first steps of this process are expensive and complex, due to the presence of many components, the condition of the gas at the end of the shift reaction make the separation easier (68).

Post-Combustion Capture

Post-combustion CO_2 capture methods are based on removing CO_2 from the waste gas. Also in this case we can use the steam to power a steam turbine. After the burner from the exhaust gas there should be some purification and filtering systems as: desulphurization, denitrogenation, and dedusting. There are many methods of post-combustion capture and they are divided accordingly to the method used to capture carbon dioxide (e.g. solvents, sorbents and membranes). Currently absorption processes are the most used. Also this process should be improved to the high energy penalty to the plant (69).

Oxy-Fuel Combustion Capture

The exhaust gas from combustion in an oxygen-enriched atmosphere (oxy-combustion) I composed mainly of carbon dioxide and water vapor. CO_2 separation is done thanks to the condensation of water vapor. The condensation temperature is higher than ambient conditions. The oxygen for combustion is produced using the air separation process, which gives an oxygen purity of about 95%. The strength points of this method are the dimension reduction, the possibility of use it in systems that already operate and, moreover, the exhaust gas flow is less (67). The weaknesses of this method are represented from the composition of the ash that can cause corrosion, fouling and leaks in the plant. This lead to have high cost in monitoring, maintenance and safety measures (69).

Direct Air Capture

Direct air capture (DAC) technologies extract CO_2 directly from the atmosphere at any location, therefore it is a completely different method compared to the ones above that are applied to CO_2 point sources. Even if it is considered still under development there are already 27 DAC projects around the world that overall capture around 0.01 [Mt CO_2/year]. Furthermore, currently 130 DAC plants are under construction at different development stages. There are two different mechanisms to capture air from the air: solid DAC (solid adsorbent in low pressure environment and temperature between 80-120 [°C]) and liquid DAC (based on aqueous basin solution in high temperature environment between 300-900 [°C]). It is a very energy intensive process (70).

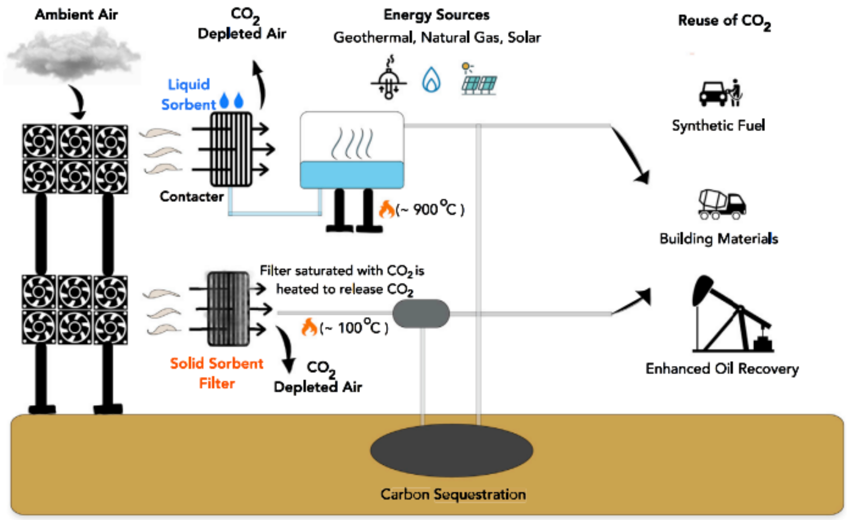


Figure 28. DAC methods (71).

TRANSPORT

Unlike other substances carbon dioxide transportation is much safer because it does not react by forming flammable or explosive mixtures. Moreover, as we said when we introduced the substance it is not directly toxic, because it is normally present in our atmosphere, the only problem is represented from high concentrations. This can happen during a catastrophic release – high quantities in short time. There is significant experience with CO_2 pipeline development and operation on land and under the sea. There are around 50 CO_2 pipelines currently operating in the US through over 8,000 [km] which transport approximately 70 [million tonnes] of CO_2 every year (72).

Usually CO_2 is transported in liquid or gaseous state. The first one is preferred due to the higher density of the substance that allow to have less storage volumes but we should take into account the energy used for its compression. **Pipelines** are worldwide the most common method to transport carbon dioxide. To use them CO_2 have to be dried before, this is done to prevent corrosion. After that it is compressed and transported. Transport of CO_2 can also be undertaken by truck, rail and ship. Carbon dioxide is carried on **trucks** or **trains** when the capture is in remote areas, far also from the storage site. Instead we use **ships** in some coastal regions or where there are offshore storage facilities (73).

STORAGE

Now we can discuss technical aspects of carbon dioxide storage. A geologic storage is defined as "*placement of CO_2 into a subsurface formation so that it will remain safely and permanently stored*"

(74). Storage CO_2 sites can be located both off and on shore. Unfortunately, the greatest capacity amount is generally located offshore as we are going to see during the last analysis, and this leads to an increase in investment costs.

5.1) CO_2 is trapping mechanisms

Carbon dioxide (CO_2) is usually stored underground as a supercritical fluid. Supercritical CO_2 means that its temperature is above 31.1 [°C] and pressure in above 72.9 [atm] (74); this temperature and pressure defines the critical point for CO_2. The earth has a temperature gradient, this mean that its temperature increases with depth, as does the pressure of the fluids in the formations. At depths higher than about 800 meters usually temperature and pressure are above the critical point of CO_2. This means that if CO_2 injected at this depth or deeper in the vast majority of cases it is supercritical in the formation. The next figure shows us the effects on the volume and density of CO_2 by assuming a surface temperature of 15 [°C] and a geothermal gradient of 25 [°C/km]:

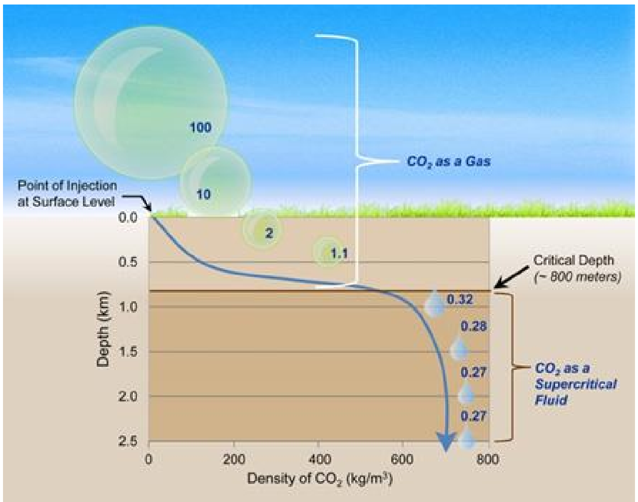


Figure 29. CO_2 pressure effects with depth (75).

But how does CO_2 remain trapped underground? There are four mechanisms that trapped the injected CO_2 (74):

- **Structural trapping**: This mechanism is the one that traps the greatest amount of CO_2. After the injection of CO_2 in suitable sites the caprock and the faults between layers act as seals, preventing the migration of the carbon dioxide.
  Diagram depicting two examples of structural trapping. The top image shows the CO_2 being trapped beneath a dome, preventing it from migrating laterally or vertically. The bottom image

shows that CO_2 is prevented from migrating vertically by the overlying seal rock and a fault to the right of the CO_2 (74).

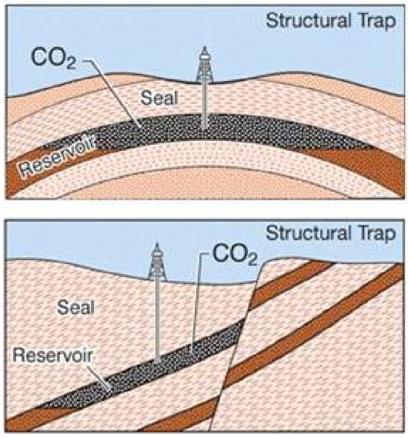


Figure 30. Structural trapping of CO_2 (74).

- **Residual trapping**: Residual trapping refers to the CO_2 that remains stuck into the rocks' pores. Indeed the rocks can act as sponges. When CO_2 is injected into the formation, it displaces the existing fluid as it moves through the porous rock. As the CO_2 continues to move, small portions of the CO_2 can stop to flow, droplets in the pore spaces which are essentially immobile.

  Diagram depicting the pockets of residually trapped CO_2 in the pore space between the rock grains as the CO_2 migrates to the right through the openings in the rock (74).

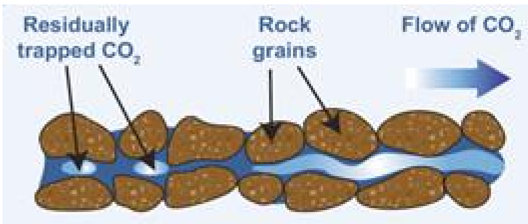


Figure 31. Residual trapping of CO_2 (74).

- **Solubility trapping**: This mechanism involves chemical reactions. A portion of the injected CO_2 will react with the brine water that is present into the ground and will dissolve into it. At the CO_2/brine water interface, some of the CO_2 molecules dissolve into the brine water and then some of that dissolved CO_2 will react with available hydrogen atoms to form HCO_{3-} (74).
- **Mineral trapping**: Mineral trapping also involves chemical reactions. It is cause by the reactivity between the dissolved CO_2 and minerals in the rocks. When CO_2 is dissolved in water there is the formation of a weak carbonic acid (H_2CO_3) and eventually bicarbonate

(HCO_3-). During long scale period this can react with surrounding rocks, permanently trapping and storing that portion of the injected CO_2.

Diagram depicting the formation of minerals on the surface of a rock grain (bottom right of image) as it reacts with the dissolved CO_2 in the brine water. The magnesium in the rock grain combines with the CO_3 in the water to produce the mineral $MgCO_3$ on the grain's surface (74).

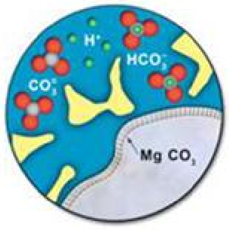


Figure 32. Mineral trapping of CO_2 (74).

Both solubility and mineral trapping are believed to be comparatively slow, potentially taking a thousand years or longer if the CO_2 is injected in a supercritical state. This mechanism could be interesting in unconventional storage types, as Carbfix method, that injects into the ground water with dissolved CO_2 inside. This accelerates a lot the chemical reactions between CO_2 and rocks (especially basalt) making the method interesting for storage.

5.2) Site selection parameters

In order to assess a storage site for long-term carbon dioxide (CO_2) storage, we have to evaluate some of the reservoir characteristics:

- **Storage Capacity:** First of all a storage needs to have enough space to contain CO_2. This is related to the pores' volume in the formation. This is function of the porosity and the thickness of the formation. The first one is a fraction of the volume of voids over the total volume:

$$\varphi = \frac{V}{V_T}$$

  If a sediment contains a mixture of grain sizes, the porosity will be lowered, the smaller particles can fill the void spaces between the larger ones. Furthermore usually it declines with depth because of compaction and cementation. The porosity should be greater than 20 % and the thickness should be at least 50 [m]. It is important to do not choose a formation with a porosity less than 10 % and a thickness under 20 [m] (76).
- **Injectivity:** This is related to the rate at which CO_2 can be injected into the subsurface. Injectivity of the CO_2 is directly related to the permeability of the formation. The permeability is representative of the properties of the porous medium alone (material). It is a measure of

the resistance to fluid flow through it. This is basically a function of the size and the shape of the openings through which the fluid moves. The dimension of permeability is [m^2] but usually it is measured in Darcy (1 Darcy = 9.87 x 10^{-9} cm^2). The permeability should be greater than 300 [mD] and should not be under 100 [mD] (76).

- **Integrity:** The integrity is the ability of the formation to confine CO_2 safely without leaks from the storage complex. The formation we choose for storage should have big layers of rock that act as seals to ensure that CO_2 does not migrate to the surface. A storage site should have also a stable geological environment over the time otherwise this property of the site will be compromised. Then it is essential in order to evaluate the integrity of a formation to monitor its stability and properties over the time because they could change.
- **Depth**: The CO_2 storage zone depth determines the state of CO_2. This is due to the variation of pressure and temperature that are mainly related to depth. Therefore the efficiency of CO_2 storage in geological media, defined as the amount of CO_2 stored per unit volume, increases with increasing CO_2 density, so we do not want to store CO_2 as a gas. There is also another phenomena related to the substance state that we should take into account if we want to prevent leaks. It is the buoyancy, which causes the migration of carbon dioxide towards the surface, and it is stronger for a lighter fluid. Density increases significantly with depth for a gaseous state of the substance, instead it generally increases slightly for a liquid or supercritical state. Anyway, more deeper the formation is the smaller will be the buoyancy. A study suggests that the ideal depth should be between 1000 and 2500 [m] and it should not be under 800 [m] or greater than 2500 [m] (76).

	Positive	Cautionary
Thickness	>100 [m]	<20 [m]
Porosity	>20%	<10%
Permeability	>300 [mD]	<100 [mD]
Depth	>1000-2500 [m]	<800/>2500 [m]

Figure 33. Site selection parameters.

5.3) Geological storage types

There are different types of storage suitable for CO_2. The first distinction is related to the storage location that can occur in both onshore and offshore settings, and each type of geologic formation presents different opportunities and challenges.

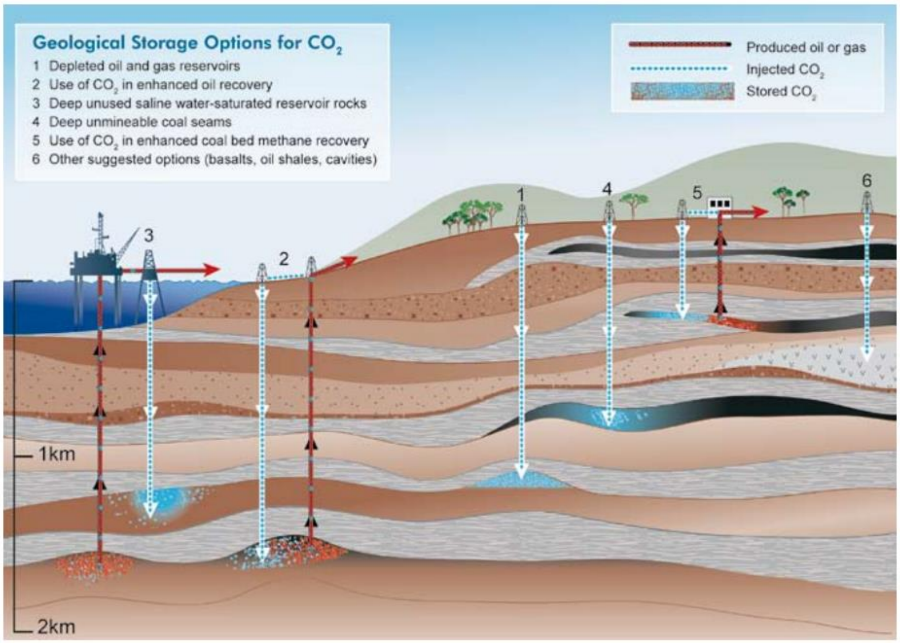


Figure 34. Different types of geological CO_2 storage (68).

- **Oil and gas fields**

  Depleted oil and gas reservoirs are the most important candidates for conventional CO_2 storage for several reasons. Firstly, the oil and gas have been trapped there for many years (in some cases for millions of years), demonstrating their integrity and safety. Secondly, due to the utilization of these fossil fuels the physical properties of most oil and gas fields have been extensively studied and characterized. Thirdly, currently the simulation through computer models is in a advanced state and it can let us save money and time during the first feasibility evaluations and for many reservoirs the oil and gas industry already have developed high accuracy models to predict the movement, displacement behaviour and trapping of hydrocarbons. Finally, some of the infrastructure and wells already in place may be used for handling CO_2 storage operations. Furthermore, if hydrocarbon fields are still in production or they finished it recently, a CO_2 storage scheme can be optimized to enhance oil production. Some reservoirs are located at depths less than a 800 [m] and this may be technically and economically feasible, but the low storage capacity for CO_2 (because it may be in the gas phase) could be problematic. Enhanced oil recovery (EOR) through CO_2 injection offers potential economic gain from incremental oil production. Of the original oil in place, 5–40% is usually recovered by conventional primary production (77). An additional 10–20% of oil in place is produced by secondary recovery that uses water flooding (78). Another study analysed the EOR operating plants underlined the average recovery percentage when different agents (also CO_2) are used for flooding. We can obtain an incremental oil recovery of 7–23% (average 13.2%) of the original oil in place (79). This is how EOR works:

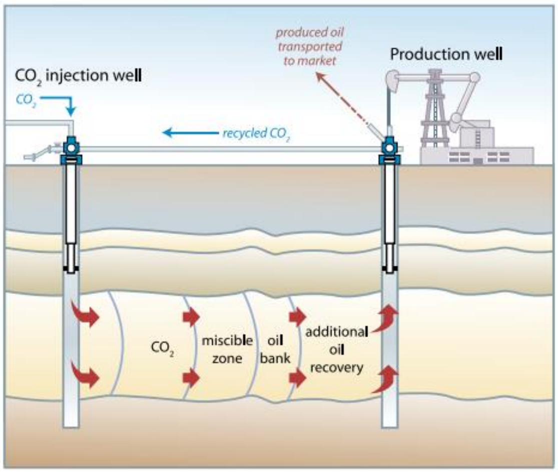


Figure 35. Enhanced oil recovery (68).

- **Saline formations**

  Deep saline formations are similar characteristics to gas and oil field, they have hosted a fluid for million of years and the fluid is trap thanks to cap rocks. They are deep carbonate (limestone or dolomite) or sandstone formations saturated with waters or brines containing high concentrations of dissolved salts (salinity tends to increase with depth). These formations are widespread and contain enormous quantities of water, but it is unsuitable for agriculture or human consumption. They could be still some applications for this water, in fact it is used by chemical industry, health spas but also for low geothermal energy production. Deep saline aquifers have the largest identified storage potential, with estimated storage capacity sufficient to store emissions from large stationary sources for at least a century (80). Unfortunately generally they are not mapped in as much detail as oil and gas reservoirs because they may occur away from oil and gas accumulations and finding and characterizing them historically has not been a fundamental part of the hydrocarbon exploration and production industry.

- **Coal seams**

  Sometimes Coal seams may be considered not convenient to drill for several reasons (geologic, technological and economic) may still can use as locations to store CO_2. Coal contains fractures that can be used as storage pores. Moreover, between cleats, solid coal has a very large number of micropores into which carbon dioxide molecules can diffuse and be adsorbed. It has a higher affinity to adsorb gaseous CO_2 than methane, the volumetric ratio of adsorbable CO_2:CH_4 ranges from as low as one for mature coals such as anthracite, to ten or more for younger, immature coals such as lignite. If CO_2 is injected into coal seams, it can displace methane, thereby enhancing CBM (Coal Bed Methane) recovery. It has the potential to increase the amount of produced methane around 90% of the gas, compared to conventional recovery of only 50% by reservoir-pressure depletion alone. Coal permeability is one of critical factors in selection of a storage site. Coal permeability varies in a big range and generally decreases with increasing depth because the pressure increase determines a cleats reduction. Most CBM-producing wells in the world are less than 1000 [m] deep.

These three types of CO_2 underground storage are the main ones, the most studied and the most feasible. Moreover it is possible to store CO_2 in other formations such as basalt and shale ones.

- **Organic shale formations**
  Shale formations are typically low-porosity and low permeability formations that work as confining zones in the vast majority of the cases. However, some shales act similar to coal, by trapping CO_2 through adsorption (adherence to the surface), subsequently releasing methane, then they are suitable for methane recovery and CO_2 storage. The large volumes of shale around the world suggest that storage capacity may be significant. If site-selection criteria, such as minimum depth, are developed and applied to these shales, then volumes could be reduced, but the very low permeability of these shales is likely to preclude injection of large volumes of CO_2.

These are the estimated capacity of the major geological storage sites around the world:

Sequestration option	Worldwide capacity (Gt CO_2)
Deep saline aquifers	100s–10 000s
Depleted oil reservoir	120
Depleted natural gas reservoir	700
Deep coal seams	140
Deep saline basalt formations	> 240
Organic shales	unknown

Table 7. Geological sites capacity (81).

5.4) Carbfix method and basalt storage

In the carbon dioxide storage field there is a new promising technology developed by an Iceland company called Carbfix. They developed an unconventional and attracting method to store CO_2 underground. The captured CO_2 is dissolved into water and then injected in underground mainly in basalt formations or other reactive rocks and together they form solid carbonate minerals that store

CO_2 permanently. The process takes 2 years from the injection (after that period more than 95% of CO_2 is stored) and this timescale initially surprised scientists. The company has developed a method that can also use seawater for the process (currently there is a demonstration field), this can be essential for coastal areas, offshore sites and water scares regions (82). How does mineralization process work?

Water charged with CO_2 is an acidic solution. This promotes the dissolution of silicate minerals that are common in basalt and peridotite. This is the reaction:

$$2H^+ + H_2O + (Ca, Mg, Fe)SiO_3 \Rightarrow (Ca^{2+}, Mg^{2+}, Fe^{2+}) + H_4SiO_4$$

The formed cations can react with dissolved CO_2. At temperatures below 300 [°C] calcium will form calcite ($CaCO_3$), above 65 [°C] magnesium will react forming magnesite ($MgCO_3$) and dolomite ($CaMg(CO_3)_2$). Below this temperature less stable hydrous Mg-carbonate can form. The way to which dissolved iron combines with dissolved CO_2 to form carbonates in the subsurface remains unclear. Under oxic conditions, Fe_{2+} oxidizes before it can react to form a divalent metal carbonate, and, thus, the mineral siderite ($FeCO_3$) is only rarely observed in modern sedimentary and basaltic rocks. The formation of the mineral ankerite ($CaFe(CO_3)_2$), however, may be favoured under certain conditions. Basalts are the most common rock on earth (5% of the surface) can naturally store more than 100 [kg] of CO_2 per m^3. On the basis of this estimate, the theoretical storage capacity of the ocean ridges is on the order of 100,000–250,000 [$GtCO_2$] orders of magnitude larger than the amount derived from fossil fuels (83).

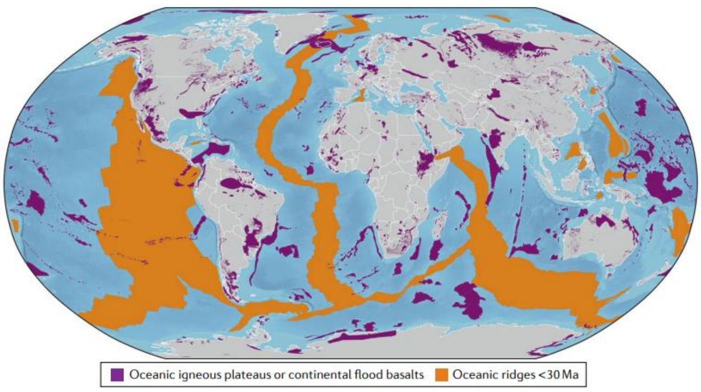


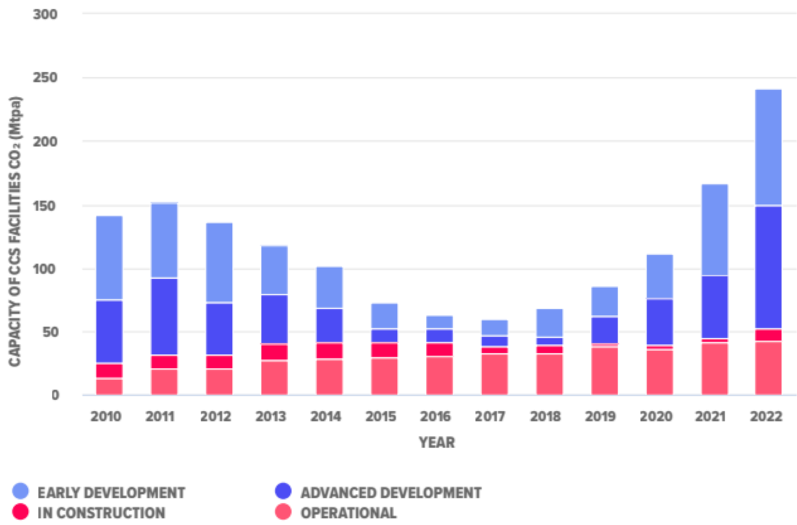
Figure 36. Feasible storage formations for in situ mineral carbonation (83).

In the first pilot project (Carbfix 2012) the water was injected at a depth of 500 [m] with a temperature range between 20 and 50 [°C]. It needs 25 tonne of water for each ton of gas dissolved. Then the second project (2014) was done by injecting the water at a depth of 800 [m] at temperature around

250 [°C]. Many of the main risks associated with the conventional injection of supercritical CO_2 into sedimentary basins also apply to carbon-mineralization projects, including the contamination of water resources and induced seismicity (83).

6) CCS STATE AND PERSPECTIVES

In the last years there has been an increase in CCS related projects. At the end of 2022 the total capacity of CCS projects was **244 [Mtpa]** of carbon dioxide that underlines an increase of 44 per cent over the year before.



Graph 20. CCS projects trend (84).

The Oil and Gas Climate Initiative (OGCI) estimates a total world storage capacity of 13954 [$GtCO_2$]. Unfortunately just a small part of it can be considered commercial resource. This map made by OGCI analyse the storage resource areas around the world:

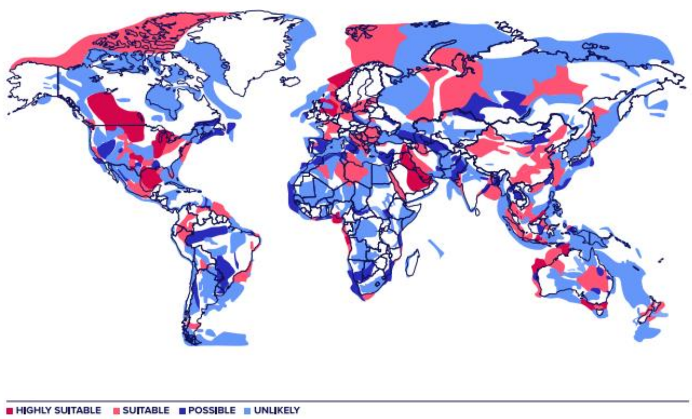


Figure 37. CO_2 storage resources around the world (85).

In the beginning the vast majority of CCS projects were full-value chain. This mean that every project had his own plant for each phase (capture, transport and storage). Nowadays, thanks to the increasing of these projects they are connected to each other in CCS networks.

This is the worldwide situation:

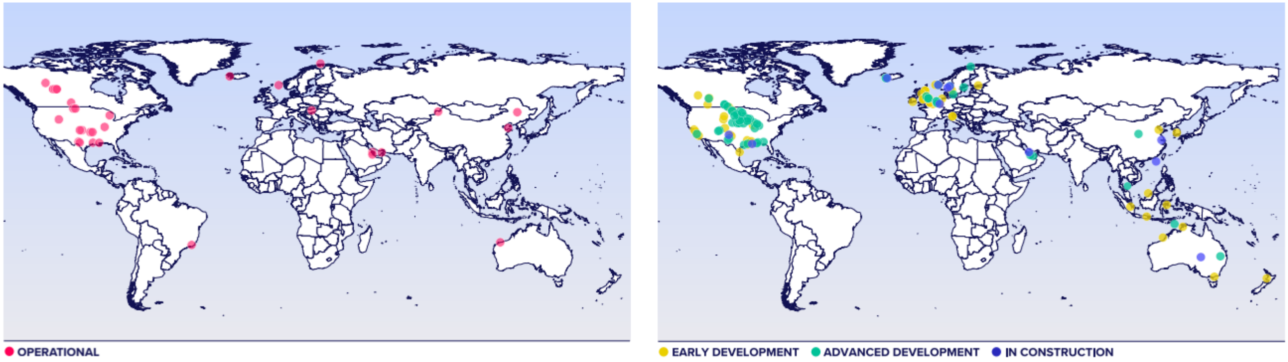


Figure 38. World CCS projects (84).

Globally there are 852 storage sites. The US continues to lead the way globally but by doing a comparison with the past it is possible to see an increase in projects especially in Europe.

6.1) Operational plants in Europe

At the end of 2022 there were 73 CCS facilities at various stages of development across Europe and UK. Within them there are only 4 operational sites that we can analyse in detail:

- **Mol Szank** field in Hungary.

  This plant is operational since 1992, and it was built for Enhanced Oil Recovery purpose. The reservoir rock is limestone and calcareous sandstone, the porosity is between 10-25 % and the waste CO_2 to inject is taken from a sweetening plant (86). Its economic limit will be reach in 2062 according to estimates (87). The capture capacity of the plant is **0.16 [Mtpa]** (84).

- **Sleipner** field in Norway.

  This is the first CCS project of the world. It is an off-shore plant, built next to the gas production plant of Sleipner west (deeper than CCS site) that produces a larger part of Norway's supply gas to European Union. It is located 240 [km] from the coastal city of Stavanger. It was made because the extracted gas contains around 9% of CO_2 but in order to sell it the percentage should be reduced to 2.5 %. Norway has an high fee on carbon dioxide emissions then it was decided to inject the CO_2 into the ground after the removal instead of emit it into the atmosphere. Nowadays the amount of injected CO_2 is under EU ETS system. It is estimated that it should have paid around 90000 € a year for the emissions. The properties of this deep saline reservoir are: (88); (89); (84)

  - Thickness is between 300 and 200 [m]
  - Porosity ranges from 27 to 42 %

- Permeability between 1 and 8 [D]
- Depth of 800/900 [m]
- A capacity of 1 [Mtpa]

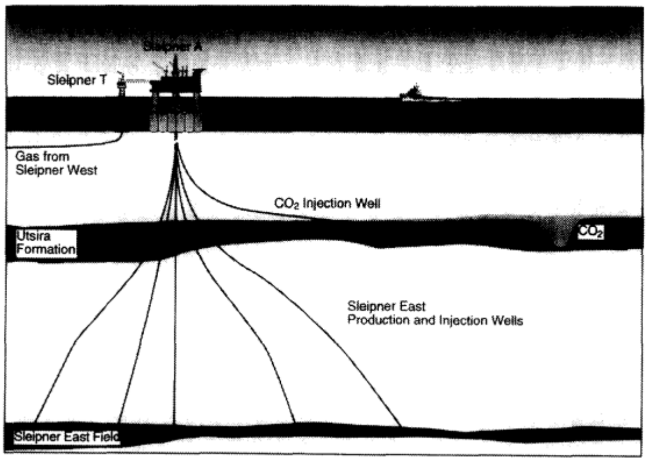


Figure 39. Sleiper CO_2 storage scheme (89).

It is estimated that Utsira formation (this is the name of the storage site) is capable to store up to 600 billion tons of CO_2. Currently there is no evidence of leaks and the cost of the injection is 17 [$/ton] (90). By 2022 it had stored 20 million tons of CO_2. Regular investigations of the sub-surface have been conducted using seismic surveying to ensure that no CO_2 is leaking from the structure to the seabed (91). The injected CO_2 properties are measured at the wellhead, but by solving flow equations it is estimated that CO_2 is stored at 104 [atm] and 48 [°C] (88).

➢ **Snohvit** field in Norway.

This plant is located in the Barents sea (north of Norway) 150 km from the coast and it is operational since 2008. This is also a deep saline reservoir. This plant was built with the same purpose of the Sleipner, because there is a gas plant next to it where the extracted gas has a CO_2 concentration around 8% and it has to be reduced in order to sell the gas. The gas was injected into Tubåen reservoir, with these properties (92); (93):

- Thickness between 45/75 [m]
- Porosity from 10 to 15 %
- Permeability ranges from 185 to 883 [mD]
- Depth of 2600 [m]
- Capacity of 0.7 [Mtpa]

The CO_2 in the reservoir were 98 [°C] and 285 [bar] (93). After a while the pressure built up faster than expected (up to 390 [bar]). The conclusion, after sampling the rock at the injection interface, was that Tubåen was not sufficiently porous and therefore not as receptive to CO_2 storage as pre-operation studies had indicated. In 2011, the injection in the Tubåen formation was stopped. The engineers started exploring the storage potential of a shallower stratum, called Stø, with a perforation at a depth of 2460 [m]. There were one problem with this, related to its proximity to gas reservoir (25 [m] above), so well engineers needed to treat it carefully. Furthermore, a new problem arose, Stø had a smaller storage potential than the original deeper Tubåen (94).

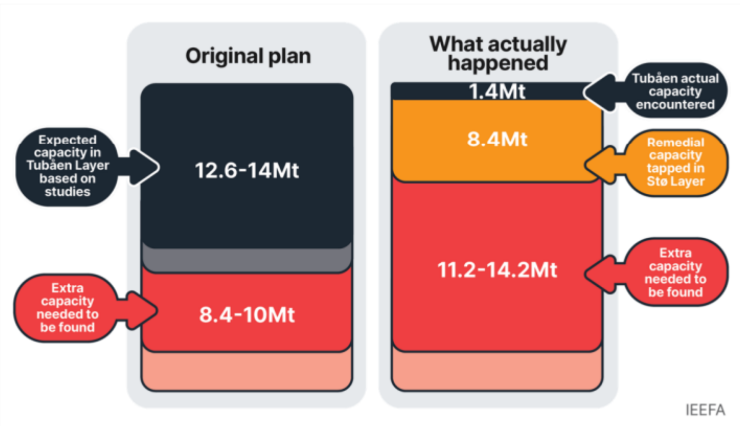


Figure 40. Snohvit CO_2 storage design plan versus implementation outcome (94).

Now Snohvit is using a third CO_2 injection site at a depth of 800 [m], after investing around 225 million [US$]. This is because engineers could be relatively certain that the second location would perform similar to the first one. The performance of the new site will require active monitoring. This case underlined that CCS operations are an amalgamation of probabilities and risks, some of which can be identified, others remaining unknown until the risk materializes (94).

- **Orca** project in Iceland.

  This project was launched in 2021 and it is the first direct air capture and storage plant of the world. This is a non conventional plant, not only for the capture method, but also for the storage one. It is called Carbfix, it is done by injecting into the subsurface a mix of CO_2 and water that will react with favourable rock formations to form solid carbonate minerals via natural processes in about 2 years. The injected carbonated water is denser than the surrounding water in the geological formation and therefore has the tendency to sink after it has been injected.

The capacity of this plant is **0,004 [Mtpa]**. It is powered with renewable energy from a geothermal plant.

6.2) Operational plant in Australia

In Australia there is just one operational plant, but it is the largest of the world. It is Gorgon carbon injection project, located in western Australia, more precisely next to Barrow Island 40 [km] off the coast. It is operational since 2019 and like the two Norway plants it is located next to a gas field and its purpose is to reduce the percentage of CO_2 inside the extracted natural gas (14% when extracted). It was projected to store 120 million tonnes of CO_2 during its lifetime. More than 8 million tonnes of CO_2 have been stored so far (95), (96). The reservoir is a deep saline formations with the following properties (97):

- Depth of 2250 [m]
- Porosity of 22%
- Permeability between 30 and 100 [mD]
- Thickness 500 [m]
- Capacity of 4 [Mtpa]

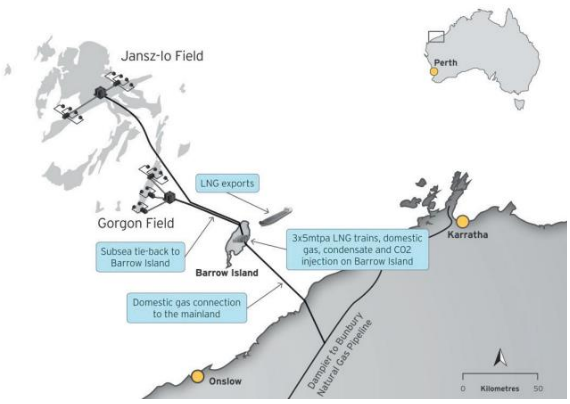


Figure 41. Gorgon field location map (97).

6.3) Capacity in Europe

In Europe a study from the Clean Energy Task force of 2023 has determined the theoretical storage potential of the area from the literature that assess country level CO_2 storage capacity. The storage sites analysed are only the conventional ones and it takes into account only countries that can store more than 10 [$GtCO_2$] (they are 17). It estimated that the **storage capacity** of Europe is between **262** and 1520 **[$GtCO_2$]**:

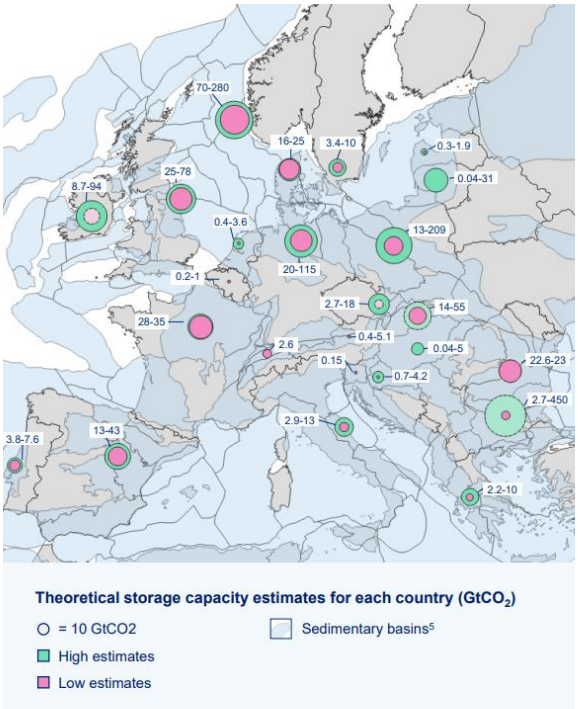


Figure 42. Europe CO_2 storage capacity (98).

In the Europe case (but also in the Australia case as we can see later) the vast majority of the capacity is related to saline formations. On the other hand the study consider the industrial emissions in Europe, then the ones we could ideally capture (without considering the new method of Direct Air Capture) and they are 780 [$MtCO_2$/year] with this distribution:

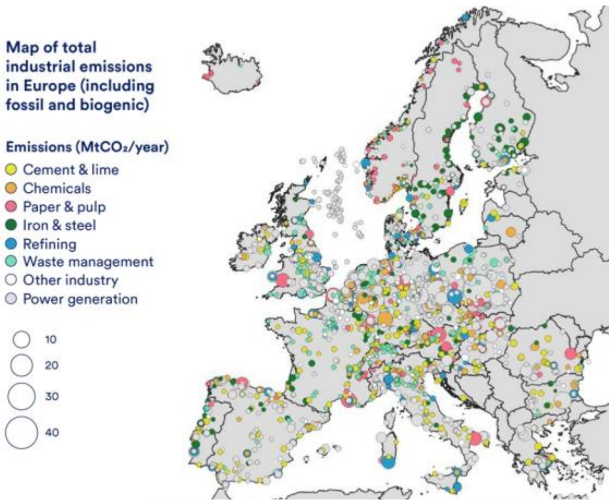


Figure 43. Europe emissions distribution (98).

The first emissions source is the energy production. Not all of this one can be captured, the study considers two scenarios. If we take into account just the conservative one it says that in 2050 we will be able to **capture and store 313 [$MtCO_2$/year]**. It is just the **40%** of the CO_2 produced from industrial emitters. This happens because usually the emission points are located in remote areas, there is a difficulty in matching them with capture points. Moreover sometimes there could be also problems related to the emissions type (even if they are concentrated) that are difficult to capture. Thus in the conservative case we can estimate to store carbon dioxide for around 820 years but we can cover less than an half of current emissions.

If we consider only plants that already exist in Europe (from operational to under development status) Europe capacity is 64,74 [MtCO_2/year] (we do not have storage capacity for all the plants under development in Europe). They currently cover only the 8.3% of the total Europe CO_2 industrial emissions.

6.4) Capacity in Australia

As far as it concerns Australia, a study developed in 2009 by a specialized task force analysed the CO_2 storage capacity of this country. The Taskforce has used a high-level, qualitative approach to ranking the basins that endeavours to account for this diversity in understanding. To determine the best or optimum geological basins for the storage of CO_2, two processes were adopted in the Taskforce's analysis. The first was to score the basins based on a range of qualitative macro-criteria related to location, geology, size, knowledge base, and so on. The second was to quantitatively determine, as far as is possible, the amount of CO_2 that can be stored within each basin. A map that shows the qualitative assessment has been developed:

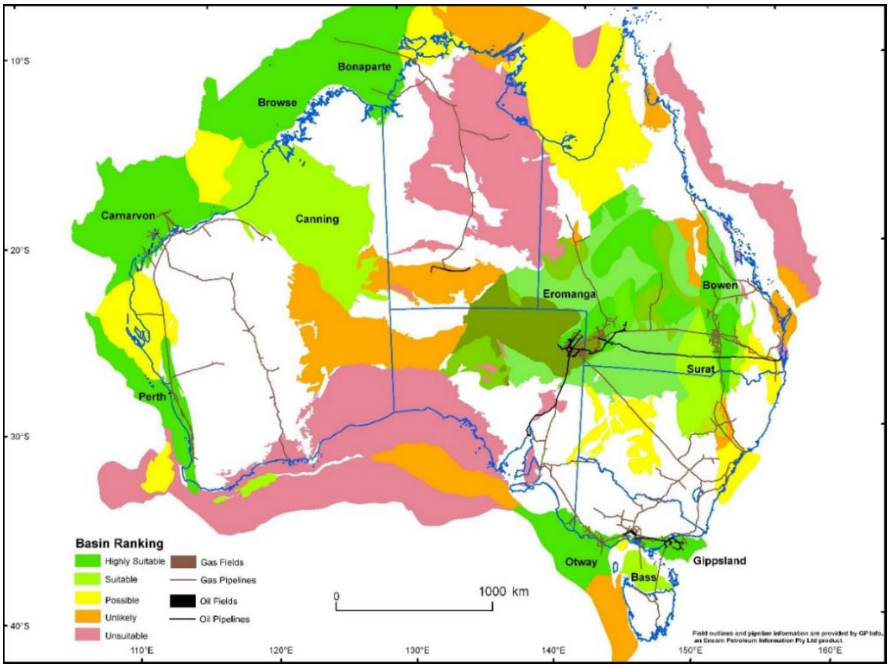


Figure 44. Australia's basins ranked for CO_2 storage potential (99).

In this study they analysed just conventional reservoirs, in particular oil and gas field and saline formation. The oil and gas field capacity was divided in off and on shore sites:

- Off-shore capacity: 15591 [$MtCO_2$]
- On-shore capacity: 938 [$MtCO_2$]

So, Australia has a total storage capacity from oil and gas fields of 16529 [$MtCO_2$] mainly represented from the off shore basins.

For the aquifer the situation is more difficult because the available data are few. A probabilistic analysis was employed to handle the inherent uncertainty in the analysis, in a similar fashion to processes employed in the petroleum industry. Each of the parameters in the analysis was described by a probability distribution then they have been combined in Monte Carlo simulations to derive probabilistic estimates of each basin's storage capacity. The data show in each basin montage at the 90%, 50% and 10% confidence levels. If we take the conservative value with 90% confidence the saline storage capacity of Australia is estimated to be equal to 226,6 [$GtCO_2$]. Thus the total **storage capacity** of the country is **243 [$GtCO_2$]**.

This study groups the emitters in hubs that can be linked to storage suitable sites. Currently the emissions in Australia are 320 [$MtCO_2$] every year. Of these one it is estimated that just **42%** can be **captured (130 [$MtCO_2$])**. We did a source-sink matching by using the maps below, we linked the hubs with the nearest storage sites:

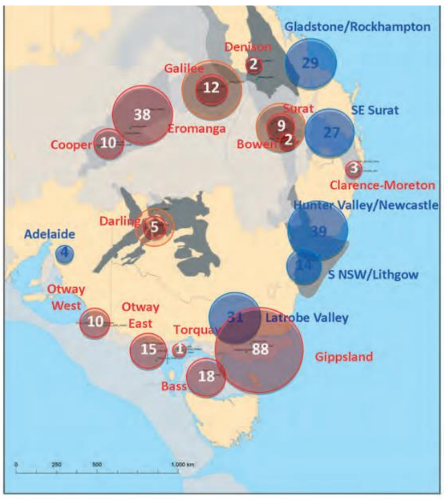


Figure 45. Emission hubs and storage sites in Australia (1)

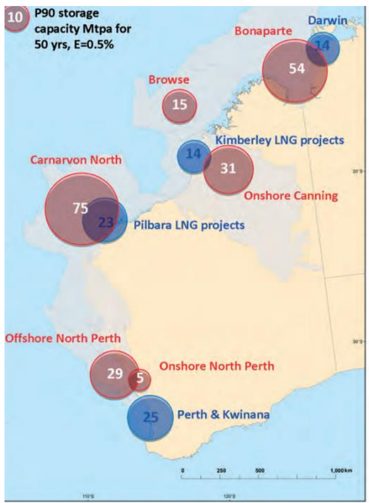


Figure 46. Emissions hubs and storage sites in Australia (2)

	Gt	Years
Gippsland Bass and Torquay	32.04	586
Othway west	4.5	2109
Galilee and Danison	9.2	556
Sorat Bowen and Clarance-Moreton	10.6	693
Off shore north and south perth	12.2	874
Carnarvor North	25.5	1730
Onshore canning and browse	23.5	4965
Bonaparte	32.2	4059
Average		**1152**

Table 8. Storing capacity of Australia sites.

With a weighted average we are able to store CO_2 at current emissions level for 1152 years, but we should take into account that we are able to capture only 40% of the total CO_2.

Currently, if we take into account all the plants in Australia (from an operational under evaluation state) the total capacity of them would be 19,9 [$MtCO_2$/yr]. All of them (6 projects) are in oil and gas fields or saline formations (84). This means that they cover just 6,2 % of Australia's CO_2 emissions. From the studies above we have a precise estimation of the storage capacity for oil and gas field within Australia territory, but also the saline formations capacity can be considered reliable because we used the most conservative value (90% of precision).

6.5) Costs in Europe and Australia

As far as it concerns costs we found a detailed study of 2018 that estimates the overall cost of a CCS plant (100). Therefore we have the costs divided into capture, transport and storage. If we hypothesize a average pipeline length of 500 [km] the costs in US dollars will be:

Capture [\$/tonCO_2]	20	110
Transport [\$/ton$CO_2$500km]	2.6	30.2
Storage [\$/tonCO_2]	1.6	18.8
Min [\$/tonCO_2]	24.2	
Max [\$/tonCO_2]	159	

Table 9. CCS plant costs (100).

The minimum is associated with this conditions: Refineries and natural gas processing; On shore pipeline with big capacity (at least 30[Mt/yr]); Depleted oil and gas field – reusing wells onshore; The maximum instead is associated with this conditions: Cement production; Offshore pipelines with small capacity; Saline formation offshore. Overall there is a costs increase for saline formation storage but and for off shore sites. The costs in local currencies would be 22-145 [€] or [35.73-235] AUS$. In the next chapter we are going to analyse and discuss the results we obtained here.

7) CONCLUSIONS

We can take the results obtained from the last chapter and analyse them in a critical way.

EUROPE	
CO_2 capacity [$GtCO_2$]	262
CO_2 captured emissions [$MtCO_2$/year]	313
Years of storage	837
Current plants capacity [$MtCO_2$/year]	64.74 (8.3%)
CCS plant cost [€/tonne]	20.5-134.5
EU ETS price [€/tonne]	85

Table 10. Europe results.

AUSTRALIA	
CO_2 capacity [$GtCO_2$]	243.13
CO_2 captured emissions [$MtCO_2$/year]	130
Years of storage	1152
Current plants capacity [$MtCO_2$/year]	19.9 (6.2%)
CCS plant cost [AUS$/tonne]	36-230
ACCU price [AUS$/tonne]	38

Table 11. Australia results.

We can see that globally the capacity of Australia is similar to the one of the entire Europe by taking the most conservative values in both cases. The theoretically years of storage are really positive results if we just look at the total years of storage, more than the one we need if we consider that in 2050 Australia and Europe declared that they want to be respectively carbon neutral and zero emissions. However, there are a variety of technical, economic, legal and social reasons that should be analysed to understand the scenario and the numbers.

Firstly those results in terms of years are so high mainly because we can capture only a small amount of the CO_2 produced, around 40% in both cases. To increase this numbers it is important to develop and invest in new capture methods, like the one from the air (Carbfix). Then, there is a big problem related to the mismatch between CO_2 sources and storage site that caused the lost of many emissions in the atmosphere. We can see from the maps in the previous chapter that in Australia the suitable storage sites are mainly located in the north/west part of the country, on the contrary the emissions come from the south/east part of it. On the other hand in Europe emission clusters and storage locations are proximate, creating relative ease of access for EU energy intensives to CO_2 storage (88), therefore the development of transportation network could be easier if compared to Australia situation. This is a problem that should be analysed for each case in order to be extremely precise, or a deep study should be conducted for the entire country by developing a model able to analyse the feasibility of a big transportation network and its costs. For this two reasons probably the available storage capacity would be lower than the estimated one.

Then we should analyse the comparison related to costs. Due to the analysis related to carbon pricing system of Australia and Europe the costs of a CCS plant was compared to the cost that currently Australia and Europe CO_2 emitters pay to underline if it would be profitable or no to invest in this technology. In both case the cost of the CCS project has a large range and the profitability is not assured. The cost for an allowance in EU ETS system is in the middle part of the CCS plant price range. This means that it could be possible to earn by investing in a CCS plant, but in some cases the CCS price would be equal or greater that buying a certificate. Unfortunately the Australian case appears to be not profitable, due to the fact that the current abatement costs are lower than build a CCS plant (the ACCU's price is in the lower part of the CCS costs range). Anyway the data used for the cost estimates are general and they can vary a lot, especially if we consider huge differences in the boundary conditions of each plant.

Moreover, it is still really difficult to make estimates related to the new technologies like Direct Air Capture and Carbfix method because we do not have sufficient data available. DAC technology could be useful to capture the carbon dioxide that is not come from pointe sources. Furthermore after the energy transition, when hopefully the source emitters will be converted we can continue to store CO_2 thanks to this technology, because we have to remember that carbon dioxide remains in the atmosphere for a long time. On the other hand the Carbfix method appears to be very promising too, due to the huge amount of basalt formation that we have on earth.

To sum up, the estimated storage capacity can ensure to store CO_2 for more years than we need but it is necessary to invest more in CCS technology in order to obtain a fall in technology cost and precise estimations about it, to be sure that that kind of projects are always profitable. The new technologies developed in the last years that try to change capture and storage method seem to be promising alternative in the CCS world and they can give a boost to this sector.

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