POLITECNICO DI TORINO

Master of Science in Climate Change
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CO_2 Emissions and Underground Storage Analysis

Towards Achieving Net-Zero Targets by 2030 and 2050

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Introduction

Climate change is currently one of the most important challenges that need to be addressed. It indicates the long-term alteration of Earth's average weather patterns, defined in the IPCC Glossary of terms as “a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use” [1]. The scientific consensus on this topic is clear: greenhouse gases (GHGs) emissions are the principal drivers, especially carbon dioxide (CO_2) ones, and they are leading to a myriad of adverse environmental and socio-economic consequences. In fact, variations in the state of the climate not only imply an unprecedent increase in atmospherics’ temperature, but also changes in the water cycle, with increased extreme events (both droughts and intense rainfalls), continued rise of the sea level (that will determine always more frequent floods), thawing of permafrost layers and melting of snow covers, glaciers and ice sheets; it also affects the oceans, which are experiencing unprecedent warming, with acidification of the water and reduction of the oxygen levels [2]. All these variations lead to undesired and dangerous effects for ecosystems and also for populations that rely on them. However, it is now a certainty that mitigation of CO_2 emissions (and also the ones of other GHGs) can curb climate change.

For this reason, nations across the world have complied to the Paris Agreement’s ambitious targets of limiting the increase in global average temperature to well below 2°C above pre-industrial levels. To comply with this target, many countries are transitioning to renewable energy sources, such as wind, solar, and hydroelectric power, to reduce reliance on fossil fuels, also supporting this transition with subsidies and incentives. Moreover, carbon pricing mechanisms like carbon taxes or cap-and-trade systems, that incentivize industries to reduce emissions by assigning a cost to CO_2 emissions, are being implemented, as well as policies promoting energy-efficient practices in buildings, transportation, and industries. Also emissions limits and efficiency standards for industries, vehicles, and appliances result necessary.

All these actions are part of the efforts needed to achieve the so called Net-Zero Targets, developed in response to the Paris Agreement, in which the year 2030 and, more critically, 2050, have emerged as pivotal milestones. The ultimate objective is to achieve net-zero emissions by 2050. This means balancing the amount of CO_2 emitted with the amount removed from the atmosphere, often through carbon capture technologies or nature-based solutions. Prominent examples include the United Kingdom and Germany committing to net-zero emissions by 2050. Moreover, there are also countries that have set 2030 targets to significantly reduce emissions, in the form of intermediate goals to help track progress in the Race to Zero. Examples include the European Union's plan to reduce emissions by 55% by 2030 and the UK's legally binding target to reach a 68% reduction by the same year. An increasing number of nations have committed to these net-zero targets: in November 2022, the amount of countries that have pledged to or are considering them scales up to 140, providing a coverage of around 90% of global emissions [3]. The success of these policies depends on political will and international cooperation, that have to be sustained by adequate financial resources to support the transition to cleaner technologies and infrastructures, and by development and deployment of new technologies.

It is within this exigent and evolving context that this master's thesis finds its purpose. This work undertakes a comprehensive analysis of the future trajectories of CO_2 emissions, with a specific focus on the industrial and power sectors. Furthermore, it explores the potential and feasibility of underground storage as a mitigating strategy in the context of the efforts to achieve Net Zero Targets and combat climate change, with an emphasis on carbon capture, storage and utilization technologies (CCUS).

In the first chapter of this thesis, historical CO_2 emissions are analyzed to evaluate socio-economic and environmental factors driving them. On this basis, SSP future projections of CO_2 emissions are reported to obtain future volumes that will be emitted throughout this century (with a focus on 2030 and 2050), also differentiating by countries and microregions of the world to evaluate which are the main emitters, and also by economic sectors to estimate the impact of the industries and the power sector.

The second chapter then takes a closer look at Carbon Capture and Storage (CCS) as a valuable option to mitigate these impending emissions. The technology is deeply analyzed, firstly from to properly understand its functioning and mechanisms, then from a global capacity point of view, to understand the actual numerical volumes that could be geologically stored. A systematic review of the existing literature and databases related to underground storage capacity of CO_2 is reported, and the evaluation spans the diverse regions of the world, as it seeks to understand the feasibility and potential of carbon capture and storage (CCS) as a means to achieve CO_2 emission reduction.

In the third chapter, the potential of CCS as a feasible strategy is evaluated, aligning it with the imperative of meeting the 2030 and 2050 Net Zero Targets. By combining the outcomes from Chapters 1 and 2, it seeks to answer a pivotal question: Can underground storage be a realistic and effective response to the challenges posed by the hard-to-abate industrial sectors and provide enough space to store all the expected emission? After this comparison, this chapter evaluates the viability of employing CCS technologies, through a feasibility analysis, to understand the costs and implications of this technology.

Finally, the fourth chapter, analyzes the opportunity posed by Carbon Capture, Utilization, and Storage (CCUS) technologies, as this approach allows not only to reduce emissions but also to utilize CO_2 as a resource. Some CCUS and CCU on-going examples are reported to highlight the viability of this technology. In this way, CCUS is evaluated as a transformative solution with the potential to not only meet targets but also reshape industrial processes and energy systems for a more sustainable future.

The evaluations reported in this thesis highlights the current urgent need for systematic and innovative strategies to address the escalating challenges of climate change. The presented findings regarding CCS and CCUS are not merely theoretical, but hold profound implications for policy formulation and industrial practices.

1. CO_2 emissions analysis

Climate change is strongly driven by human activities (such as deforestation, the burning of fossil fuels, and industrial processes) that release greenhouse gases into the atmosphere, with CO_2 emissions being responsible for the majority of the human-induced global warming. All the data that are exposed and presented in this historical analysis are taken from the IEA-EDGAR CO_2 database released by the Publications Office of the European Union (Luxembourg, 2022) [4]. As it is possible to see from Figure 1, the sectors that are the largest sources of CO_2 emissions are the power industry (burning of fossil fuels for energy production), transportation and the industrial one.

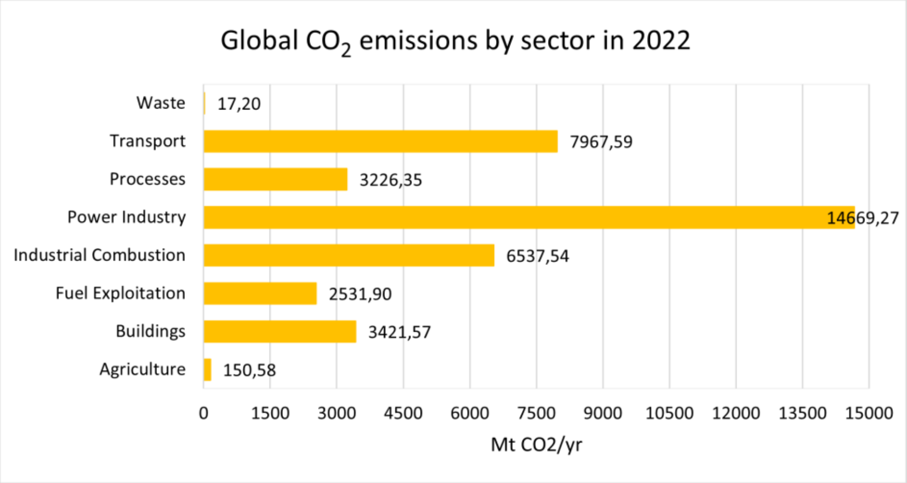


Figure 1: Global CO_2 emissions by sector in 2022, from the IEA-EDGAR CO_2 database

In the mentioned sectors, emissions have largely increased in the last 50 years at a global scale, as visible in Figure 2.

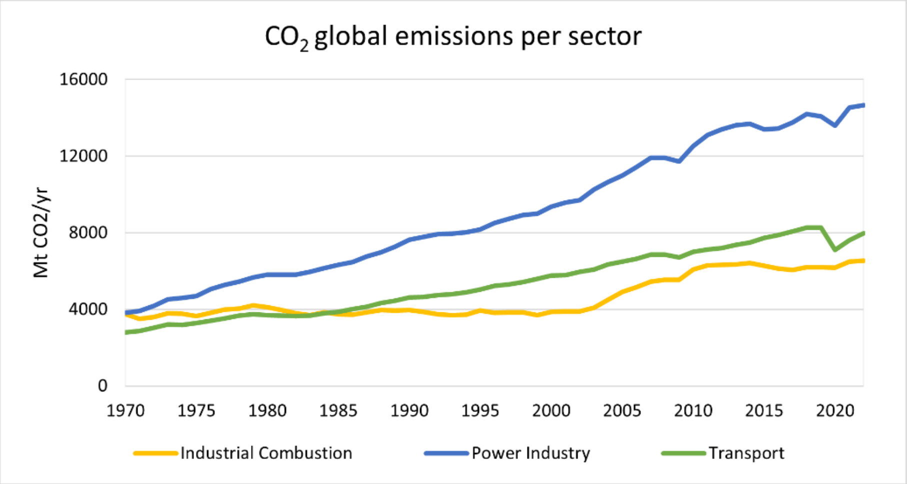


Figure 2: Three highest CO_2 emitting sectors globally, from the IEA-EDGAR CO_2 database

These represent the hard-to-abate industries, which are sectors of the industry, like steel, cement, petrochemical, glass production and power generation, that face significant challenges in reducing their carbon dioxide emissions to mitigate climate change. These industries' emissions are usually deeply integrated into their processes, that inherently emits large volumes of CO_2 in the atmosphere (like cement production, steel manufacturing, and chemical production), making it difficult to eliminate or reduce them using currently available technologies. Replacing or retrofitting these facilities with low-carbon alternatives (some of these industries lack easily implementable low-carbon alternatives) can be expensive and technically challenging, affecting their competitiveness in the global market. Accounting for a large part of the global CO_2 annual emissions, the reduction of their share of emissions results to be fundamental to achieve global climate goals and reach the Net Zero Targets for 2030 and 2050, and it requires efforts from governments, industries, and stakeholders to develop and implement effective solutions. To evaluate the amount of CO_2 that these sectors will emit in the future it is firstly necessary to analyze the CO_2 emissions of different countries in the world during the last 50 years (in which these industries have grown).

1.1 Historical CO_2 emissions

Global emissions of CO_2, as shown in Figure 3, have significantly increased in the last 50 years.

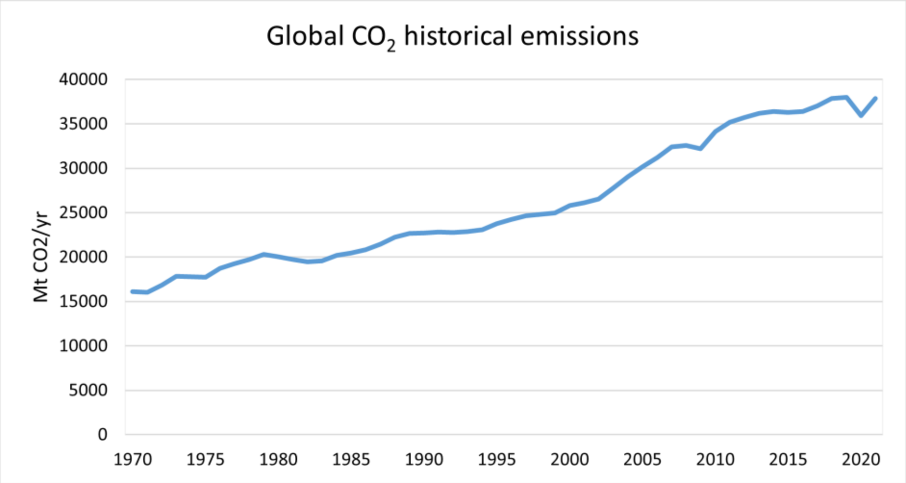
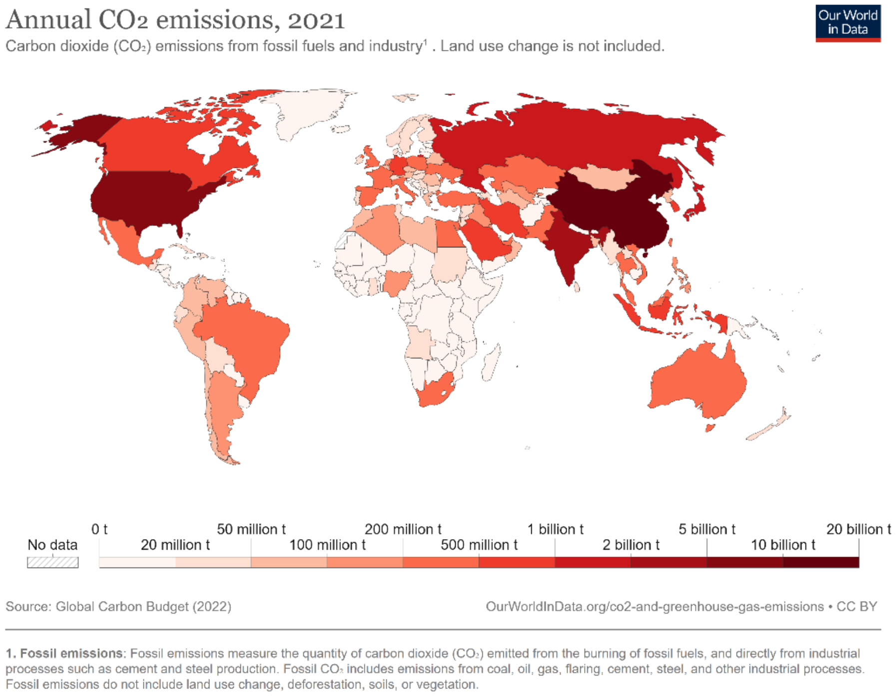


Figure 3: Global CO_2 historical emissions, from the IEA-EDGAR CO_2 database

This paragraph analyzes the emissions of CO_2 that have been recorded all around the world in the last 50 years, highlighting the key factors contributing to the disparities in these data. CO_2 emissions data are available and can be analyzed in terms of annual emissions per capita, by country, and even adapt them considering trades and the economical flows of imports and exports. In this research all the data on CO_2 emissions that are taken into account are related to the country where they are produced (defined 'production-based' emissions), not to the one where relative final goods or services are then consumed (defined 'consumption-based' emissions).

Figure 4, taken from Our World in Data [5], shows the total annual global emissions of CO_2 recorded in 2021: the strong disparities in the amount of CO_2 emitted from the different areas of the world are evident.



Source: Global Carbon Budget (2022)

OurWorldInData.org/co2-and-greenhouse-gas-emissions • CC BY

1. Fossil emissions: Fossil emissions measure the quantity of carbon dioxide (CO_2) emitted from the burning of fossil fuels, and directly from industrial processes such as cement and steel production. Fossil CO_2 includes emissions from coal, oil, gas, flaring, cement, steel, and other industrial processes. Fossil emissions do not include land use change, deforestation, soils, or vegetation.

Figure 4: Annual CO_2 emissions of 2021, from Our World in Data

China results to be by far the largest emitter between all the different countries, as it accounted alone for an important share of the total global emissions (34% in 2021), followed by the United States (13%), India (7%), Russia (5%) and Japan (3%). This highlights the previously mentioned strong disparity between the contributions of different countries in global emissions, since in 2021 only five of them (out of the 208 accounted in the IEA-EDGAR CO_2 dataset [4]) accounted for 62% of the total global emissions. In Figure 5 are reported the timeseries of the CO_2 emissions of this five countries in the last 50 years.

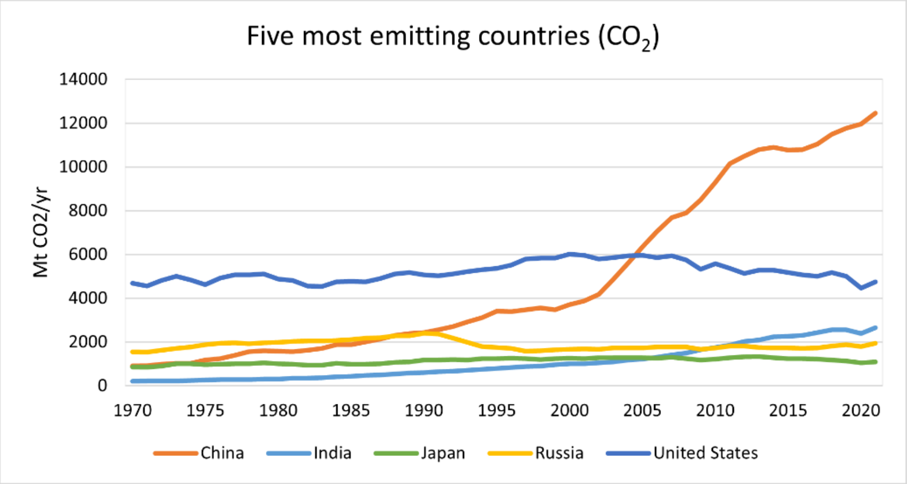


Figure 5: CO_2 historical emissions of the current five most emitting countries, from the IEA-EDGAR CO_2 database

Looking from a broader perspective, it is interesting to notice that there is also a strong imbalance between the different continents, which is possible to notice from Figure 6, that shows the timeseries of the CO_2 emissions of the continents in the last 50 years.

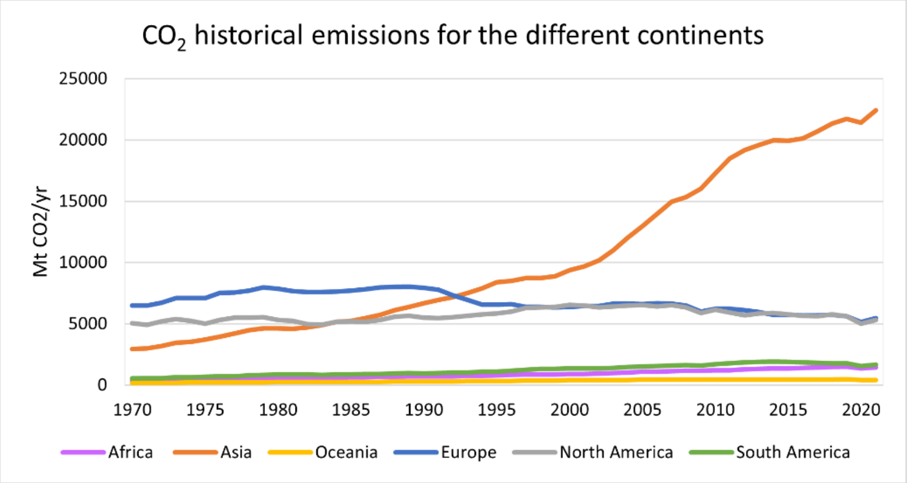


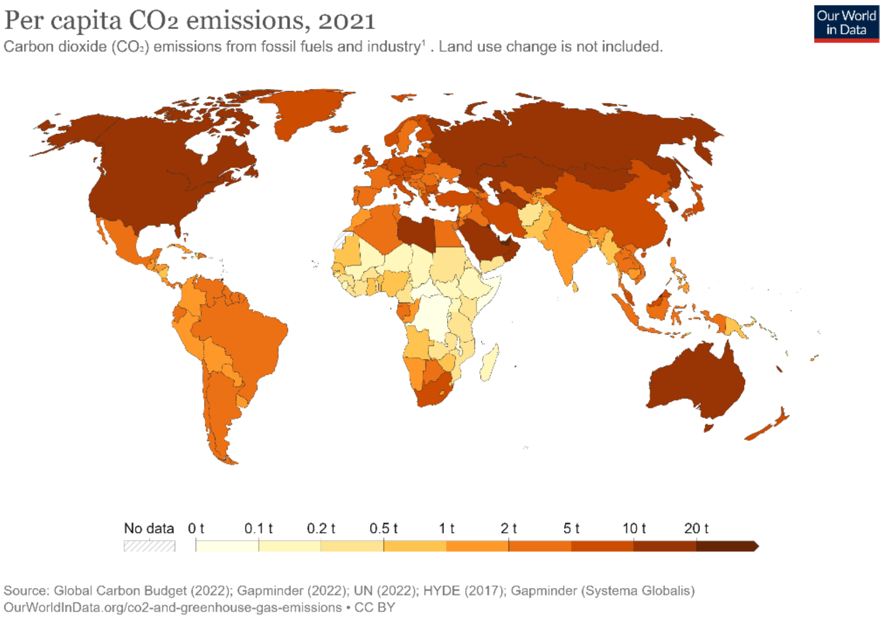
Figure 6: CO_2 historical emissions of the continents, from the IEA-EDGAR CO_2 database

Asia has the largest share of emissions (61% of the total in 2021). Then follow Europe and North America, each accounting for 15% and 14% of global emissions. On the other hand, South America, Africa and Oceania are all fairly small emitters, respectively accounting for 5%, 4% and 1% of global emissions each.

This great disproportion is due to the fact that the total annual CO_2 emissions are affected by factors like location, population size, industrial activities and energy sources: for example, countries in tropical regions have higher shares of emissions related to processes like deforestation, agriculture and energy use for cooling, with respect to countries located in other areas. For completeness it is important to take these aspects into account.

As visible from the data, countries with high population densities, such as India and China, can experience elevated emissions due to increased energy demand, transportation needs and industrial activities. On the contrary, areas with vast territories and small populations, like Australia, may have lower overall emissions due to reduced urbanization and industrialization. However, for the case of Asia for example it would be incomplete not to relate its large share of global emissions to the fact that this continent hosts around 60% of the total global population.

In this context it is very helpful to evaluate the contribution of each country in a standardized form, dividing its total emissions by its population, obtaining the annual CO_2 emitted by every country per capita, which is reported in the global visualization of Figure 7, taken from Our World in Data [5].



Source: Global Carbon Budget (2022); Gapminder (2022); UN (2022); HYDE (2017); Gapminder (Systema Globalis)
OurWorldInData.org/co2-and-greenhouse-gas-emissions • CC BY

Figure 7: Per capita CO_2 emissions in 2021, from Our World in Data

With this type of data it is possible to notice that China's situation is factually not one of the worsts, considering that it has an estimated population density of 150.4 people per square kilometer (2021) [6]. Moreover, among the countries that have substantially low per capita CO_2 emissions, some of them, especially the poorest ones in Sub-Saharan Africa, like Niger, Chad, and the Central African Republic, may experience a rapid emissions growth in the future as they industrialize, that could be dangerous if not controlled. The largest per capita CO_2 emitting countries generally corresponds to the highest oil producers, especially the ones with low population sizes with respect to their surfaces, and they are mainly located in the Middle East. This outlines a typology of emitting country that has the capacity to produce a very negative impact on climate change, since the stress that it produces compared to its population results way too heavy. However, oil-producing countries usually have relatively small populations, so that their total annual CO_2 emissions result to be low compared to other countries with higher inhabitants. In Figure 8 and Figure 9 are reported the timeseries of the last 50 years' per capita emissions of the five largest per capita CO_2 emitting countries, and also the timeseries of their total annual emissions in the last 50 years, in which it is possible to confirm the previous statements.

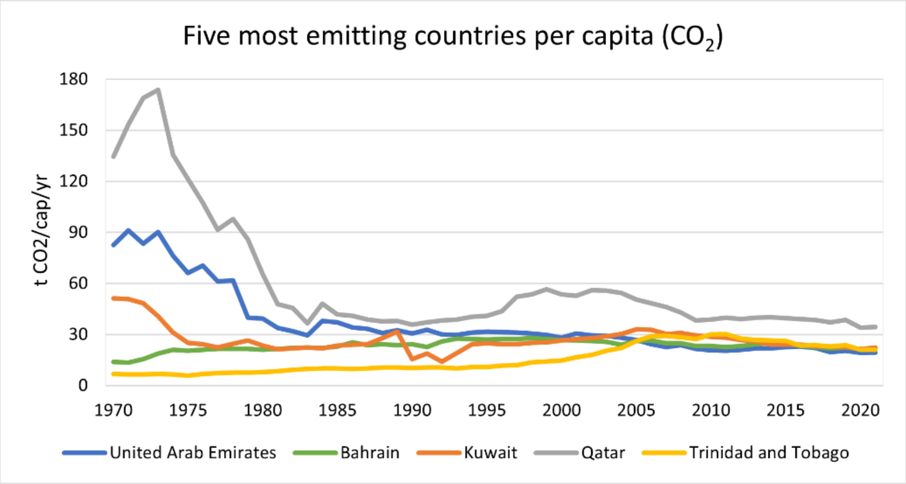


Figure 8: Timeseries of per capita CO_2 emissions of the five largest per capita CO_2 emitting countries, from the IEA-EDGAR CO_2 database

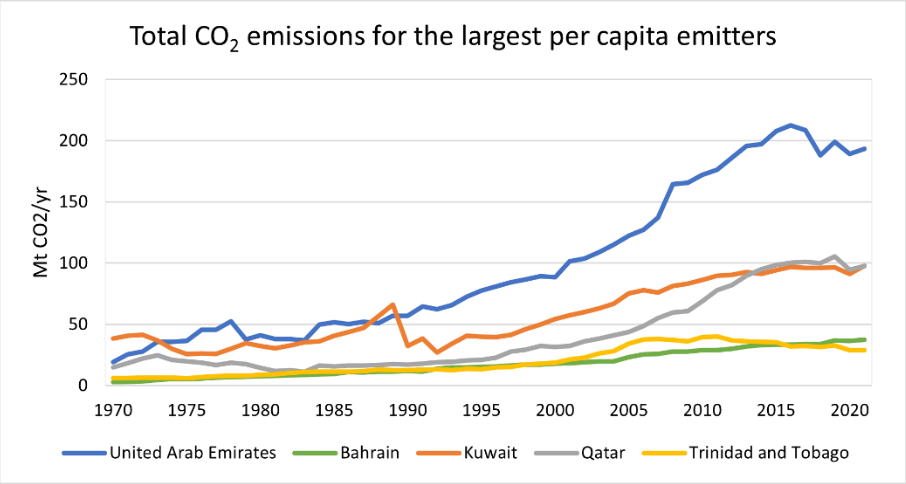


Figure 9: Timeseries of CO_2 emissions of the five largest per capita CO_2 emitting countries, from the IEA-EDGAR CO_2 database

The actual worst situation results to be the one of more populous countries with relatively high per capita emissions, that leads to large amounts of total emissions, like in the United States, Australia, Canada, Germany, Japan and Russia (which are all reported in Figure 10).

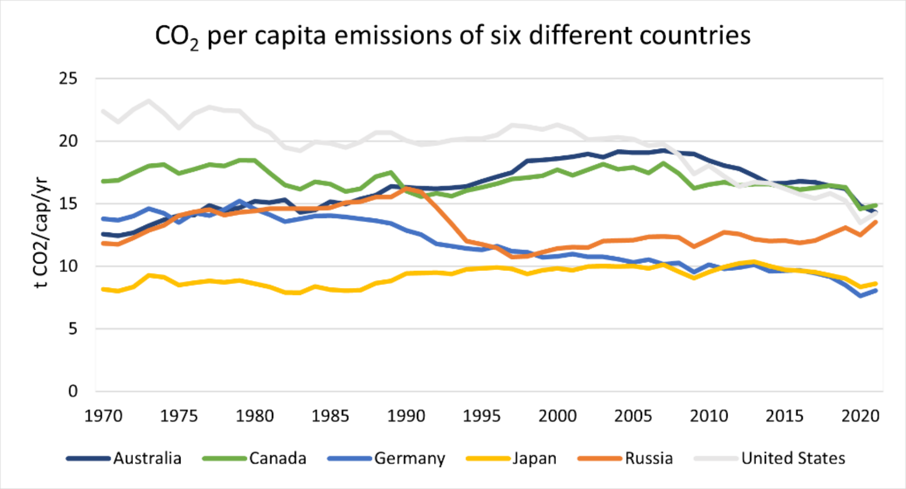


Figure 10: Timeseries of per capita CO_2 emissions of six highly emitting countries, from the IEA-EDGAR CO_2 database

In addition to per capita emissions it is also useful to analyze the Carbon Intensity of GDP, which is an indicator that expresses the amount of annual CO_2 emissions of a country with respect to its GDP. This parameter can provide information regarding the environmental and economic sustainability of the investigated country, and by tracking changes in its value over the years, it’s possible to assess whether the nation is making progresses in reducing its CO_2 emissions relative to economic growth, and whether its environmental policies are being effective. Comparing "Carbon Intensity of GDP" (CIGDP) among different countries can help evaluate which ones are making progresses in emissions reduction compared to others, as it is possible to see in Figure 11 for some countries with different situations.

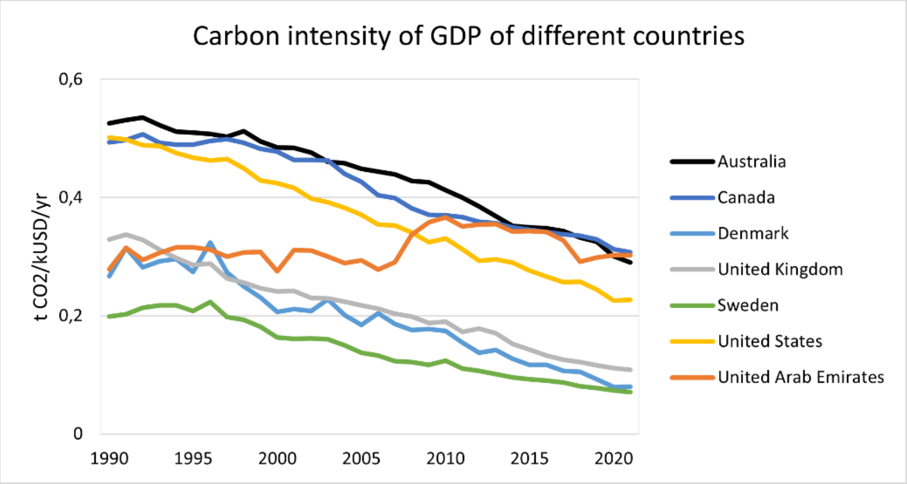


Figure 11: Carbon intensity of GDP of different countries, from the IEA-EDGAR CO₂ database

When the value of CIGDP results to be high, in the case of a poor country it indicates that the nation is facing significant environmental challenges due to a lack of resources to invest in cleaner technologies, while for a wealthy country it indicates that it is producing a high amount of CO_2 emissions relative to its GDP, which is usually a sign of economic inefficiency and significant environmental impacts. As deducible from Figure 11, examples of this negative behavior are the United States, Canada and Australia, the first one has a high GDP but also a high CIGDP due to its great reliance on fossil fuels in some sectors of industry and in transportation. Moreover it is also possible to notice that countries that are major oil producers, like the United Arab Emirates, result to have a strongly increasing CIGDP value.

On the contrary, a low value of CIGDP could either reflect an overall low level of economic development (in case of poor countries like the ones in Africa) or in the case of wealthy countries, it also indicates that the nation is producing a relatively low amount of CO_2 emissions compared to its economic activity, suggesting an improvement in energy efficiency and reductions in the environmental impacts of its economic activities. Examples of this positive behavior are reported in Figure 11 with countries like Sweden, Denmark and the UK, of which the first one has a high per capita GDP and one of the lowest levels of carbon intensity in the world for industrialized countries. This highlights that this kind of countries have managed to decouple economic growth and CO_2 emissions, mainly thank to two different mechanisms: decoupling energy utilization and economic development (GDP increases and simultaneously the total energy use remains flat, or even falls) and replacing fossil fuels with low-carbon energy.

1.1.1 World's largest emitters

This section is devoted to the analysis of how the emissions are distributed in the different compartments of the economic system of the countries that resulted to be the largest global CO_2 emitters, which are reported in Table 1.

Table 1: CO_2 emissions of industrial sectors of the thre highest emitting countries, from the IEA-EDGAR CO_2 database

Country	Sector	Mt of CO_2 in 2021	% of the total
China	Power Industry	5539,91	44%
	Buildings	671,92	5%
	Transport	955,46	8%
	Other industrial combustion	3349,64	27%
	Other sectors	1949,38	16%
	Total	12466,32	100%
India	Power Industry	1265,18	48%
	Buildings	188,60	7%
	Transport	286,23	11%
	Other industrial combustion	665,95	25%
	Other sectors	242,81	9%
	Total	2648,78	100%
United States	Power Industry	1611,58	34%
	Buildings	571,06	12%
	Transport	1647,57	35%
	Other industrial combustion	672,62	14%
	Other sectors	249,25	5%
	Total	4752,08	100%

The first one resulted to be China, with a total of 12466,32 Mt of CO_2 emitted in 2021, followed by United States (4752,08 Mt) and then India (2648,78 Mt). From Figure 12, Figure 13 and Figure 14 it is possible to visualize the timeseries of CO_2 emissions of the different sectors in China, Unites States and India in the last 50 years.

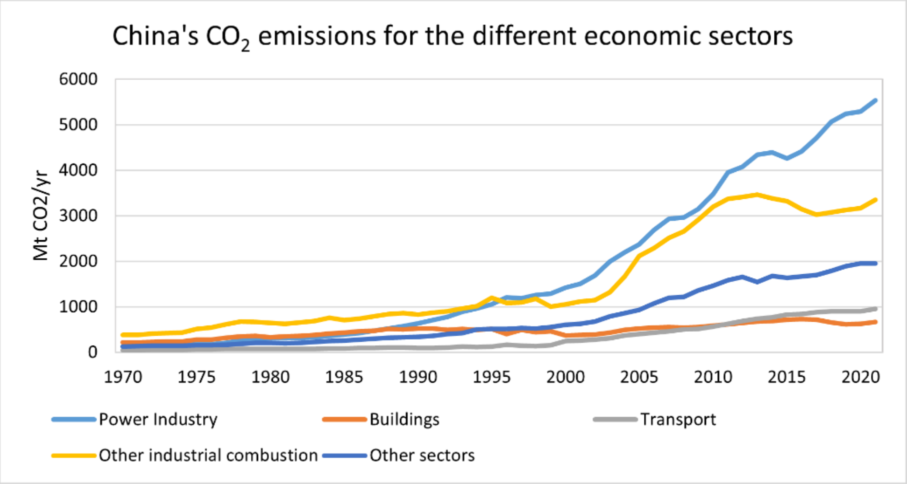


Figure 12: Timeseries of CO_2 emissions of the different industrial sectors in China, from the IEA-EDGAR CO_2 database

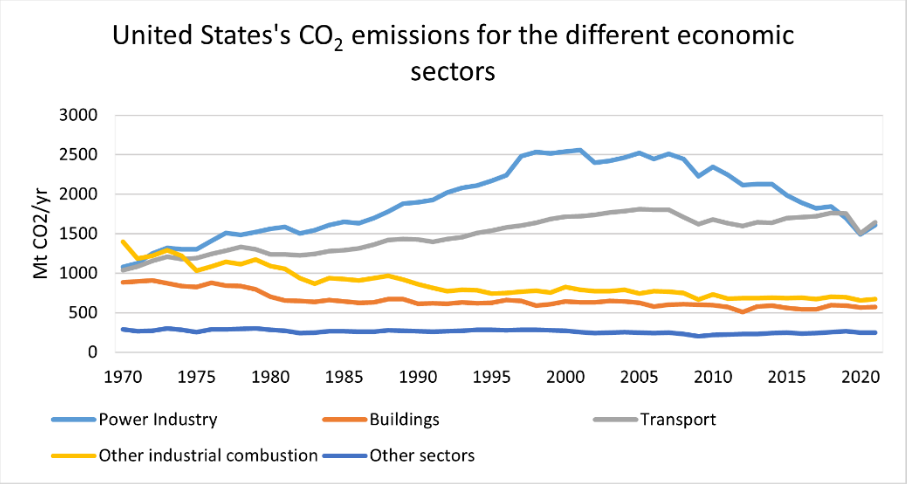


Figure 13: Timeseries of CO_2 emissions of the different industrial sectors in the United States, from the IEA-EDGAR CO_2 database

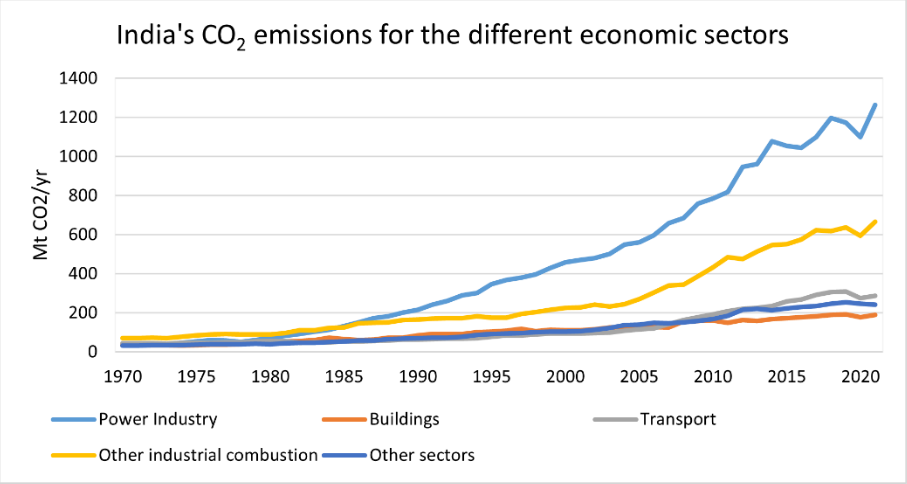


Figure 14: Timeseries of CO_2 emissions of the different industrial sectors in India, from the IEA-EDGAR CO_2 database

It is very important to notice that these three countries are the three largest coal- and oil- consuming countries, as well as three of the fifteen largest consumers of natural gas [7]. The highly intensive use of fossil fuels is in fact the main driver of these countries' emissions. It is also useful to analyze in more details their specific cases.

In China the sector that contributes the most to emissions is the industry, that also includes energy production and manufacturing. The energy industry results to be the biggest contributor to greenhouse gases emissions: the production has the largest share, and most of China's electricity is obtained from coal, which in 2019 accounted for 65% of the generation mix, while energy consumption, according to the 2016 Chinese Statistical Yearbook published by China's National Bureau of Statistics, includes 64% coal, 18.1% crude oil, 5.9% natural gas, 12.0% primary electricity and other energy [8] [9]. Following there is the transportation sector, which is rapidly growing due to increased motorization, and the construction one, which requires a considerable amount of energy for lighting, heating, and cooling of buildings. In the shares of the industry sectors, some that resulted very impacting are: manufacturing industry at 19%, cement at 15% and steel from 15% to 20% (2020).

In the United States, CO_2 emissions results to be mainly distributed between the transportation and the energy sector, accounting together for almost 70% of the total emissions. The ones from transportation primarily come from the combustion of fossil fuels for all the different means of transport, of which more than 94% is petroleum based (mainly gasoline and diesel) [10] [11]. The energy sector includes electricity generation and fossil fuels consumption for heating and cooling in residential and commercial buildings. Electric power includes emissions from electricity production, of which 79% comes from combustion of fossil fuels, mostly coal and natural gas [10] [11]. The industrial sector also plays a substantial role, especially emissions originated from manufacturing processes and energy-intensive operations.

CO_2 emissions in India are the third highest in the world and they mainly derive from coal [12] [13]. In this country, a quarter of these emissions are from the industrial sector (mainly for production of cement and iron and steel). However, the major contribution is again from the energy sector, in fact the country's heavy reliance on coal for power production contributes significantly to its emissions. Also India's transportation sector (as noticeable in Figure 14) is a growing source of emissions due to the increasing number of vehicles on the road, that heavily rely on fossil fuels like gasoline and diesel.

1.2 Future projections of CO_2 emissions

This last section of the chapter is dedicated to the estimation of the amounts of CO_2 that will be emitted in the near future. A particular interest is given to the years 2030 and 2050, since they are the pivot ones in the path towards Net Zero Targets. When making future projections, it is very important to consider the inherent uncertainties of this process, and for this reason it is useful to comprehend more than just one possible scenario. In this context, a set of scenarios was developed in the IPCC Sixth Assessment Report, consisting of the SSP on which they are based, and the expected 2100 level of radiative forcing (ranging from 1.9 to 8.5 W/m^2) [14].

1.2.1 Shared Socioeconomic Pathways

The idea behind the Shared Socioeconomic Pathways (SSPs) is to obtain climate change scenarios of projected socioeconomic global developments up to 2100, in order to deduce GHGs emissions scenarios. To obtain this result scientists estimated ranges of possible future evolutions, accounting for many factors affecting emissions, like mitigation, pollution control and socioeconomic and political development, allowing to have standardized versions of all the used socioeconomic assumptions (population, GDP, poverty, etc…) across modeled representations of each scenario. In Figure 15 (taken from [15]) are reported the five different SSPs, arranged with respect to the challenges they imply, in terms of mitigation and adaptation.

Figure 15: Shared Socioeconomic Pathways definition, from [15]

Going from left to right (increasing adaptation challenges) there are firstly SSP1 ("Sustainability (Taking the Green Road)") and SSP5 ("Fossil-fueled development

(Taking the Highway)”), which represent potential futures of either green- or fossil-fueled economic and social growth, in which incomes globally register a great increase, and inequality at different scales is importantly reduced [14].

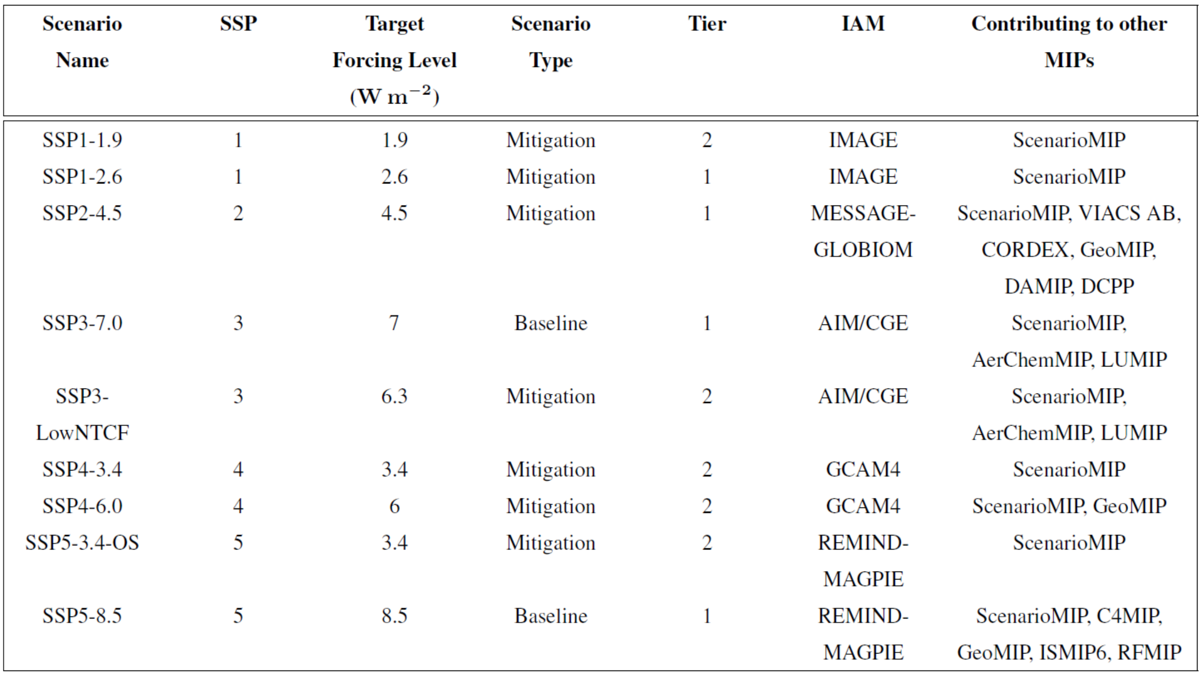
SSP1 results to be the most sustainable scenario, in which there are important behavioral changes and improvements in energy efficiency that lead to a great reduction in the demand for resource and energy intensive agricultural materials. On the other hand, SSP5 results as the highest emitting scenario, in which there is a significant growth cause by the increasing importance of competitive markets, stakeholders participation and innovative solutions to produce technological developments, and also the high investments in education, health and institutions to increase human and social capital. However, this growth results to be at the expense of environmental impacts deriving from abundant fossil fuels utilization and adoption of resource- and energy- intensive lifestyles.

Then there is SSP2 (“Middle of the road”), which is an intermediate scenario, with modest population growth and slower abatement of disparities in income levels between countries, where social, economic, and technological patterns do not shift significantly from historical ones. Food consumption is expected to rise and power generation do not shift from dependance on fossil fuels, resulting in increasing emissions. The environment experiences degradation, although there are some improvements that then leads to a decline in the intensity of resource and energy use. Endeavors to mitigate air pollution maintain current paths, with developing economies catching up late to high-income ones, finally leading to a decrease in pollutant emissions.

Lastly there are SSP3 (“Regional rivalry (A Rocky Road)”) and SSP4 (“Inequality (A Road Divided)”), that are characterized by inequalities between or within countries. These scenarios both depict futures with low global GDP growth, mainly occurring in high-income countries, while population increases in low and middle income ones. In SSP3 there are strong concerns about competitiveness and security, and countries prioritize the need of achieving their energy and food security goals to the detriment of larger scales developments. Moreover energy systems in SSP3 see a comeback of coal reliance, that does not occur in SSP4, in which the high tech energy and economy sectors develop and receive more investments.

For each SSP, different RF could be met depending on what policies and practices are implemented over the century, and each end of century forcing value is combined with a SSP, on the basis of significant experimental coverage. Out of all these possible scenarios produced by Integrated Assessment Models (IAMs), nine were chosen for the Scenario Model Intercomparison Project for CMIP6, and are divided in Tier 1 and Tier 2, all reported in Table 2, which is taken from [16], that comprehend both baseline and mitigation cases.

Table 2: SSP scenarios, taken from [16]



Scenario Name	SSP	Target Forcing Level $(\mathrm{W\,m^{-2}})$	Scenario Type	Tier	IAM	Contributing to other MIPs
SSP1-1.9	1	1.9	Mitigation	2	IMAGE	ScenarioMIP
SSP1-2.6	1	2.6	Mitigation	1	IMAGE	ScenarioMIP
SSP2-4.5	2	4.5	Mitigation	1	MESSAGE-GLOBIOM	ScenarioMIP, VIACS AB, CORDEX, GeoMIP, DAMIP, DCPP
SSP3-7.0	3	7	Baseline	1	AIM/CGE	ScenarioMIP, AerChemMIP, LUMIP
SSP3-LowNTCF	3	6.3	Mitigation	2	AIM/CGE	ScenarioMIP, AerChemMIP, LUMIP
SSP4-3.4	4	3.4	Mitigation	2	GCAM4	ScenarioMIP
SSP4-6.0	4	6	Mitigation	2	GCAM4	ScenarioMIP, GeoMIP
SSP5-3.4-OS	5	3.4	Mitigation	2	REMIND-MAGPIE	ScenarioMIP
SSP5-8.5	5	8.5	Baseline	1	REMIND-MAGPIE	ScenarioMIP, C4MIP, GeoMIP, ISMIP6, RFMIP

Tier 1 include SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, and provides a complete range of forcing targets, that result similar to the ones in the RCPs of CMIP5. Tier 2 includes SSP1-1.9, SSP3-LowNTCF, SSP4-3.4, SSP4-6.0, and SSP5-3.4-Overshoot (OS) and provides deeper investigations on the effect of mitigation and adaptation policies that fall between the Tier-1 forcing levels [16]. For the aim of this research, scenarios of Tier 2 are not necessary, and for this reason, only results from Tier 1's scenarios will be analyzed.

1.2.2 Future projections

The data related to future CO_2 emissions, reported in this part of the chapter are taken from the SSP Public Database [17]. CO_2 emissions value at the end of the century result to change significantly across different scenarios (from -14.000 Mt/yr to 126.000 Mt/yr), as reported in Table 3.

Table 3: Future global emissions of CO_2 in the selected SSP scenarios, from the SSP Public Database

Future Global Emissions of CO_2 [Mt CO_2/yr]			
Scenario	2030	2050	2100
SSP1-1.9	22847	2050	-13890
SSP1-2.6	34734	17964	-8618
SSP2-4.5	43476	43462	9683
SSP3-7.0	52847	62904	82726
SSP5-8.5	55297	83298	126287

Moreover, in Figure 16 are reported the trends of future scenarios until 2100. They are characterized by different behaviors: SSP1s have a defined downward trajectory, SSP2-4.5 and SSP5-8.5 peak in a given year and decrease (respectively in 2040 and 2090), and SSP3-7.0 presents a continued growth in emissions.

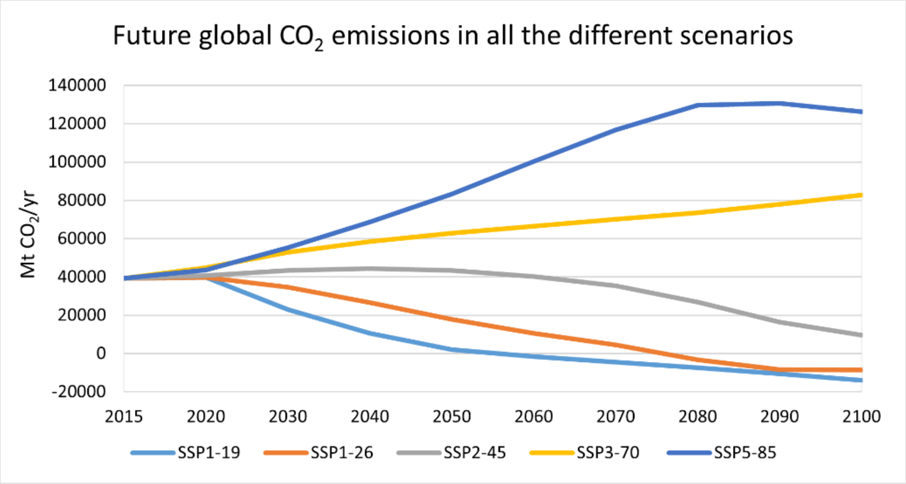


Figure 16: Future global CO_2 emissions in the selected SSP scenarios, from the SSP Public Database

In this first graph also the trend of the SSP1-1.9 is reported, since it represents a policy-relevant scenario that reaches a global mean temperature increase of ~1.4°C by the end of the century, resulting to be in line with the goals of the Paris Agreement [16]. This represents the trend that should be followed to be compliant with the targets that are currently being set, and it is possible to notice the strong discrepancies between its data and all the other scenarios. In the following part of the paragraph, SSP1-1.9 will not be reported, since its outcomes result to be very unlikely to happen.

The highest peak is registered in 2090 by the SSP5-8.5, and it is coherent with a scenario that models a world with a fossil-fuel driven development. On the other hand, the lowest values are in the SSP1-2.6 scenario, that first reports net negative emissions already in 2080, confirming that SSP1s are the more sustainable possible futures.

In Figure 17, Figure 18, Figure 19 and Figure 20 are reported global CO_2 emissions trajectories for the different sectors of the economy in the four Tier-1 scenarios.

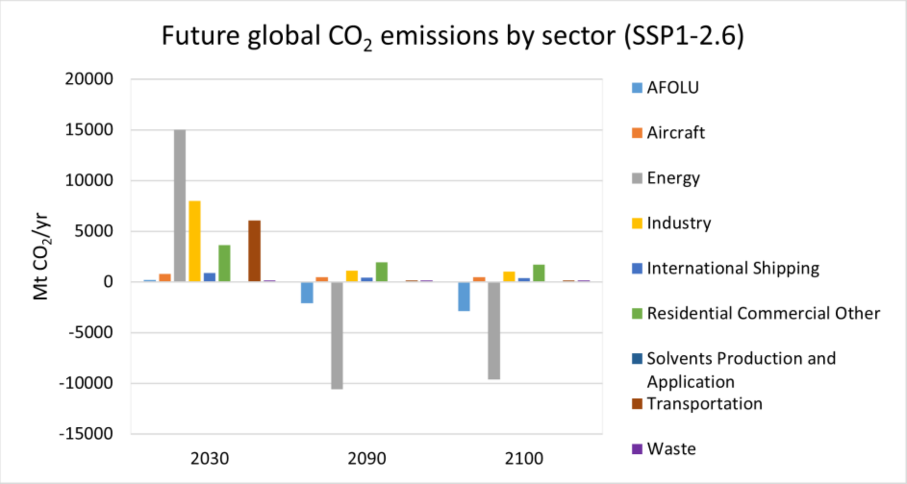


Figure 17: Future global CO_2 emissions by sector in SSP1-2.6, from the SSP Public Database

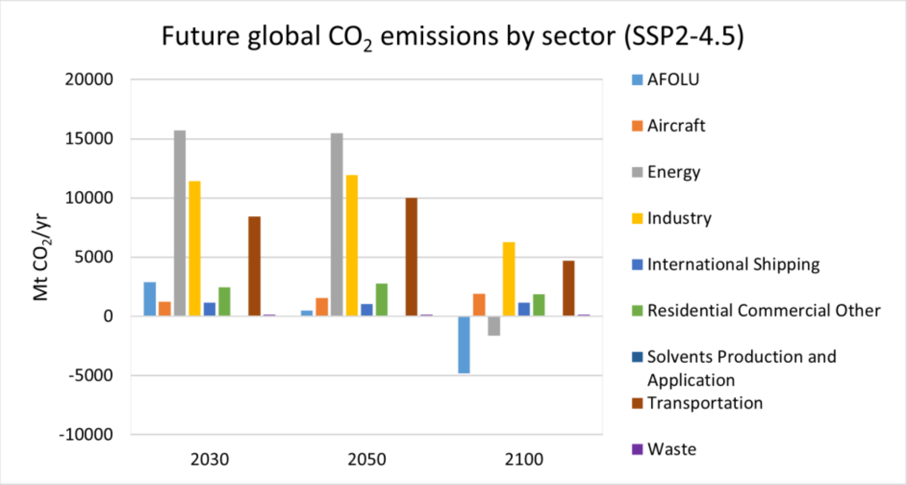


Figure 18: Future global CO_2 emissions by sector in SSP2-4.5, from the SSP Public Database

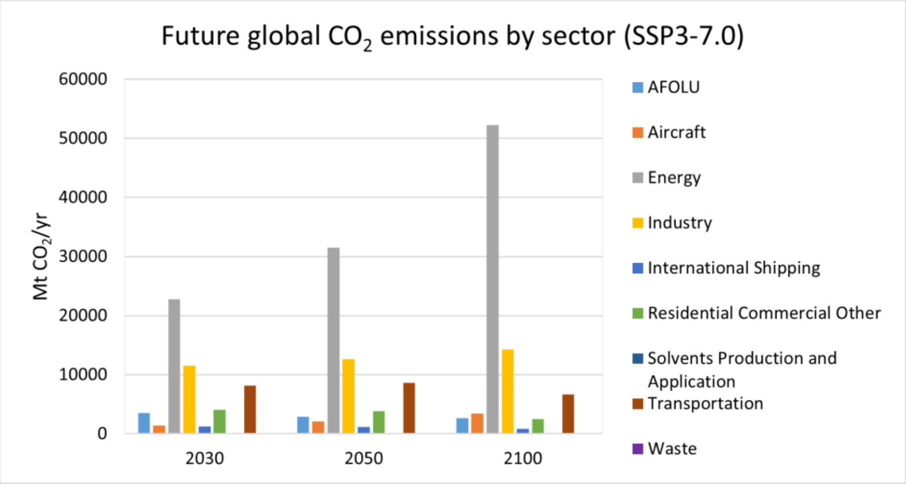


Figure 19: Future global CO_2 emissions by sector in SSP3-7.0, from the SSP Public Database

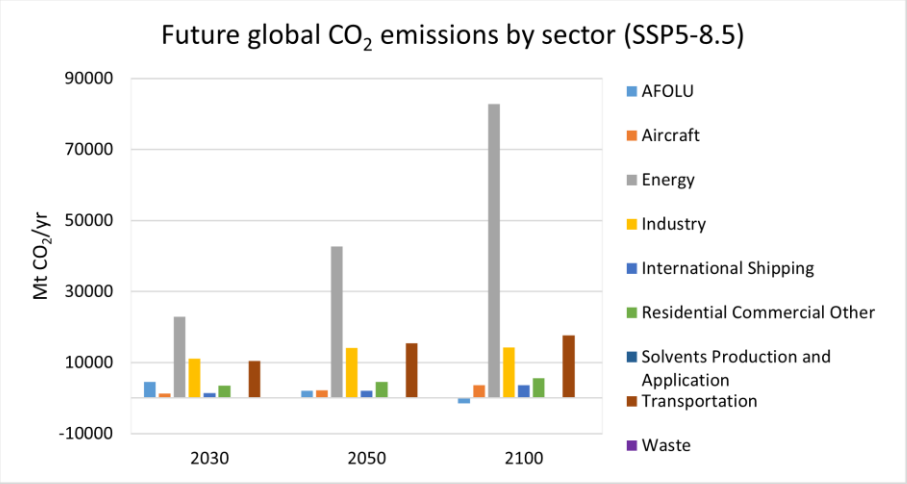


Figure 20: Future global CO_2 emissions by sector in SSP5-8.5, from the SSP Public Database

In all the scenarios, CO_2 emissions are mainly influenced by the energy, industry and transport sectors. Another important feature that comes out is the importance of agriculture and land-use in achieving negative emissions profiles. The numerical data of the energy and industrial sectors are reported in Table 4.

Table 4: Future global CO_2 emissions of the most impacting economic sectors in the selected SSP scenarios, from the SSP Public Database

Future global CO_2 emissions of the most impacting sectors				
		2030	2050	2100
SSP1-2.6	Energy	14990	6146	-9632
	Industry	8003	3751	1011
SSP2-4.5	Energy	15703	15461	-1638
	Industry	11422	11949	6275
SSP3-7.0	Energy	22808	31484	52225
	Industry	11569	12656	14260
SSP5-8.5	Energy	22888	58363	82807
	Industry	11070	14430	14247

For what concerns the spatial distribution of future CO_2 emissions, after the evaluations made in the previous section, it results useful to analyze the globe as divided in five macro regions, as defined by the SSP Database [17], inside of which there are countries with similar behaviors (different type of countries grouped in five contributions): ASIA (the highest global emitters), REF (countries from the reforming economies of eastern Europe), OECD (OECD 90 and EU member states and candidates), MAF (Middle East and Africa) and LAM (Latin America and the Caribbean). In Table 5 are reported the emissions of these five regions in the various scenario for 2030, 2050 and 2100.

Table 5: CO_2 future emission in the selected SSP scenarios for the five macro regions, from the SSP Public Database

CO_2 future emissions [Mt CO_2/yr]				
Region	Scenario	2030	2050	2100
ASIA	SSP1-2.6	15971	7868	-1074
	SSP2-4.5	18099	17507	3607
	SSP3-7.0	22642	26801	30246
	SSP5-8.5	22359	34226	43327
LAM	SSP1-2.6	2096	1503	-347
	SSP2-4.5	2431	2731	-1096
	SSP3-7.0	2623	3324	5122
	SSP5-8.5	3101	5006	6102
MAF	SSP1-2.6	3799	2691	117
	SSP2-4.5	4571	6551	4966
	SSP3-7.0	5064	7674	17856
	SSP5-8.5	5424	12309	33572
OECD	SSP1-2.6	8834	4783	-4888
	SSP2-4.5	10739	11104	3189
	SSP3-7.0	13374	15388	17981
	SSP5-8.5	14399	21155	33246
REF	SSP1-2.6	2175	1442	-378
	SSP2-4.5	2383	2465	742
	SSP3-7.0	3030	3613	4599
	SSP5-8.5	2814	4259	4181

The importance of the regional reductions or growths of emissions seems to change significantly in the different scenarios. In general, as also seen in the historical data, future CO_2 emissions are significantly influenced by progresses in Asia (in which China and India determine most of its contribution), that results again as the highest contributor (its trends for the different scenarios are reported in Figure 21).

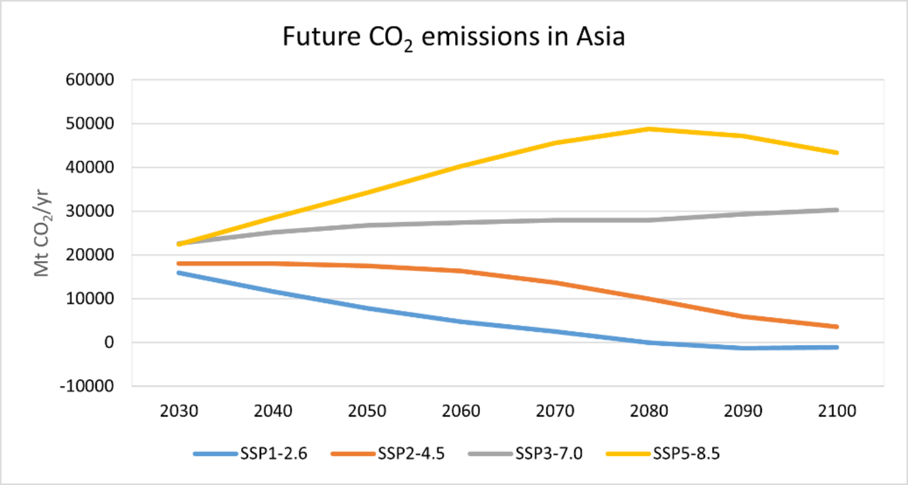


Figure 21: Future CO_2 emissions in the selected SSP scenarios for ASIA, from the SSP Public Database

In SSP1-2.6, emissions in Asia arrive at zero by 2080. In this scenario, strong mitigating efforts occur globally, and the largest carbon decrease occurs in the OECD, as noticeable in Figure 22, and all regions arrive to net negative by the end of the century.

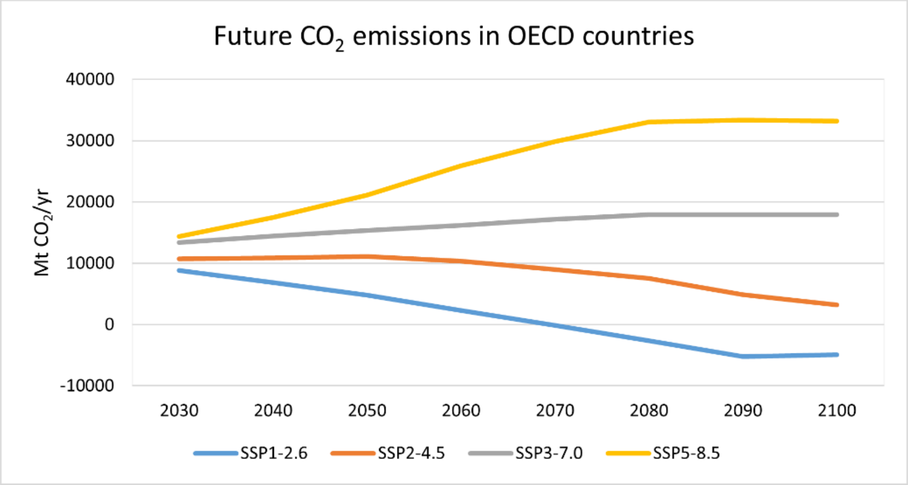


Figure 22: Future CO_2 emissions in the selected SSP scenarios for OECD countries, from the SSP Public Database

In SSP2-4.5, Asian emissions peak in 2030, and all the other macro regions record reductions, except for Africa, due to its late development and industrialization. The only region to arrive at net negative emissions by the end of the century results to be LAM, thanks to biomass-based energy production and carbon sequestration [16]. A general increase of emissions occurs in all the regions in both SSP3-7.0 and SSP5-8.5.

In all the scenarios, the sectors that result to have the highest shares of emissions in the various regions are always the same, for this reason only the results of one scenario (SSP3-7.0) will be reported to present them. In Figure 23, Figure 24, Figure 25, Figure 26 and Figure 27 are the future CO_2 emissions of the various sectors of the economy for the five chosen regions.

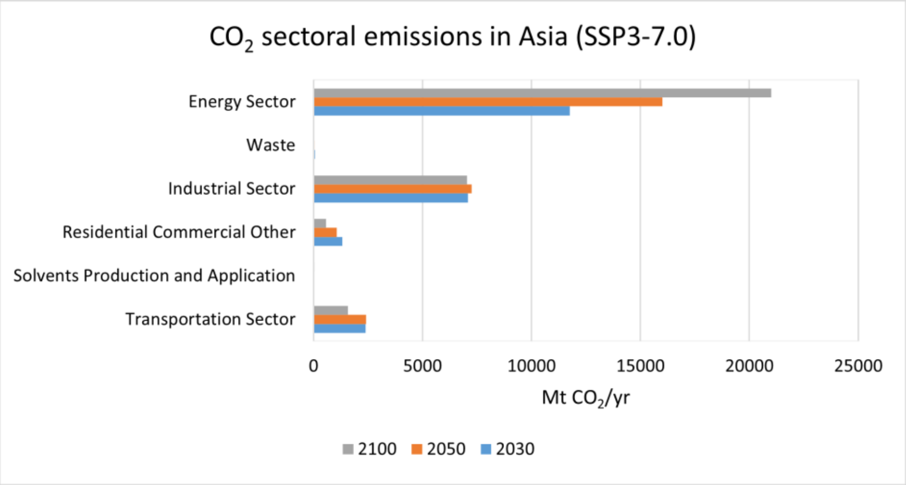


Figure 23: Future CO_2 emissions of the various economic sectors in SSP3-7.0 in Asia, from the SSP Public Database

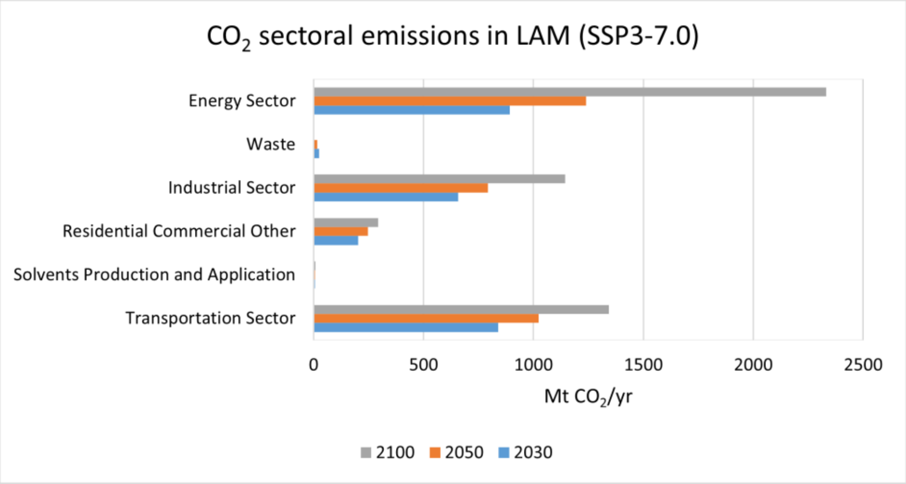


Figure 24: Future CO_2 emissions of the various economic sectors in SSP3-7.0 in LAM, from the SSP Public Database

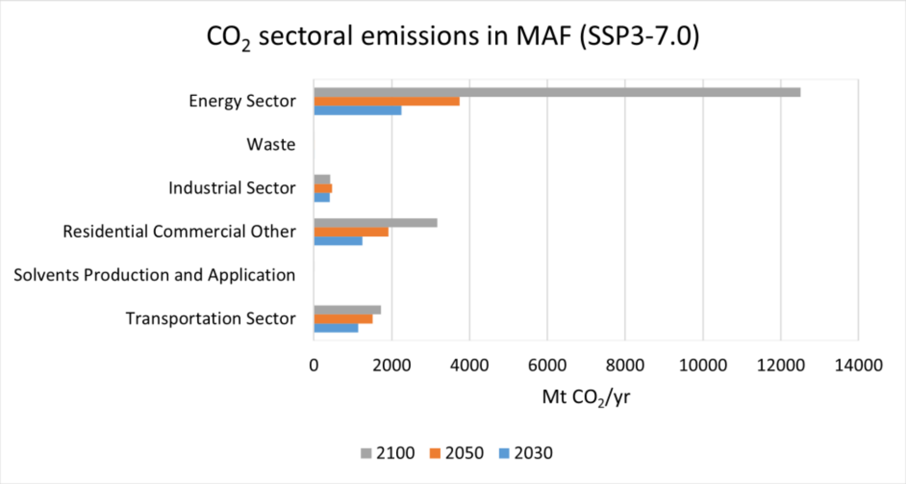


Figure 25: Future CO$_2$ emissions of the various economic sectors in SSP3-7.0 in MAF, from the SSP Public Database

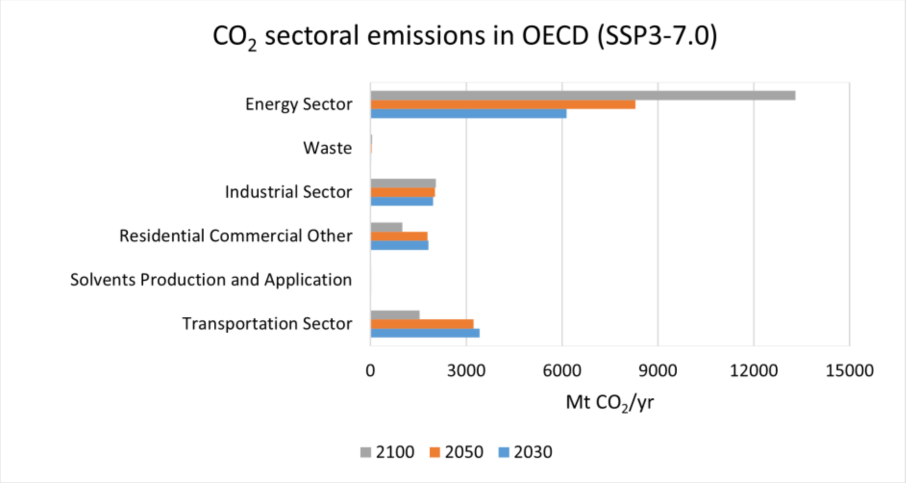


Figure 26: Future CO$_2$ emissions of the various economic sectors in SSP3-7.0 in OECD, from the SSP Public Database

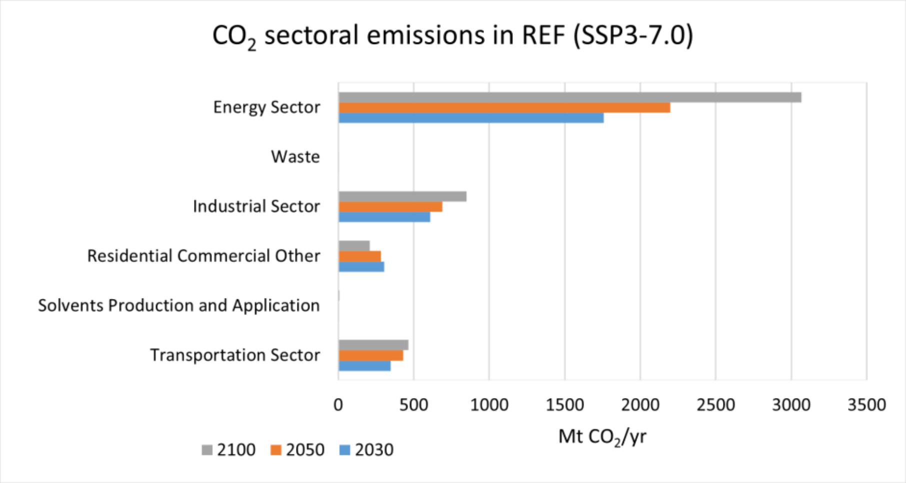


Figure 27: Future CO$_2$ emissions of the various economic sectors in SSP3-7.0 in REF, from the SSP Public Database

The main emitter results the energy sector, followed by the industry (sometimes overtaken by the transport sector). For this reason, in Table 6 are reported the CO_2 emissions that are estimated for these two sectors in 2030, 2050 and 2100 in the five different macro regions.

Table 6: Future CO_2 emissions for the industry and energy sector in the selected SSP scenarios for the five macro regions, from the SSP Public Database

Region	Scenario	Sector	2030	2050	2100	Region	Scenario	Sector	2030	2050	2100
ASIA	SSP1-2.6	Industry	4463	1633	165	OECD	SSP1-2.6	Industry	1536	835	312
		Energy	8049	3118	-1912			Energy	3596	1562	-5707
		Total	12512	4752	-1747			Total	5132	2397	-5395
	SSP2-4.5	Industry	6909	7063	2543		SSP2-4.5	Industry	1915	1933	1173
		Energy	8069	6040	-1194			Energy	3752	4353	357
		Total	14978	13103	1349			Total	5668	6287	1529
	SSP3-7.0	Industry	7089	7245	7042		SSP3-7.0	Industry	1965	2013	2047
		Energy	11770	16007	21011			Energy	6138	8292	13310
		Total	18859	23252	28053			Total	8103	10305	15357
	SSP5-8.5	Industry	5878	6118	4185		SSP5-8.5	Industry	2168	3040	4549
		Energy	11944	20664	31954			Energy	5958	10891	20287
		Total	17823	26781	36139			Total	8126	13932	24837
LAM	SSP1-2.6	Industry	563	339	93	REF	SSP1-2.6	Industry	500	272	70
		Energy	640	259	-594			Energy	1150	682	-591
		Total	1204	598	-501			Total	1650	954	-522
	SSP2-4.5	Industry	632	442	215		SSP2-4.5	Industry	726	679	134
		Energy	809	1121	-1671			Energy	1128	1114	403
		Total	1441	1563	-1455			Total	1854	1793	537
	SSP3-7.0	Industry	657	792	1145		SSP3-7.0	Industry	610	688	851
		Energy	893	1238	2332			Energy	1757	2200	3068
		Total	1550	2030	3476			Total	2367	2888	3918
	SSP5-8.5	Industry	860	1120	1087		SSP5-8.5	Industry	671	900	603
		Energy	1238	2132	3505			Energy	1510	2540	2918
		Total	2098	3253	4592			Total	2181	3440	3521
MAF	SSP1-2.6	Industry	940	672	371						
		Energy	1555	523	-828						
		Total	2495	1195	-456						
	SSP2-4.5	Industry	1239	1832	2210						
		Energy	1945	2833	467						
		Total	3185	4665	2677						
	SSP3-7.0	Industry	406	471	420						
		Energy	2251	3746	12504						
		Total	2657	4216	12925						
	SSP5-8.5	Industry	1494	2937	3824						
		Energy	2237	6494	24142						
		Total	3730	9431	27966						

2. Underground storage of CO_2 analysis

This chapter is devoted to the quantification of the underground storage capacity that is available to host CO_2 all around the world. Underground storage is the last step of the Carbon Capture and Storage (CCS) process (in Figure 28 is reported a schematic of this process, taken from [18]), that consists firstly in collecting and capturing CO_2 either directly from the atmosphere or from large point sources.

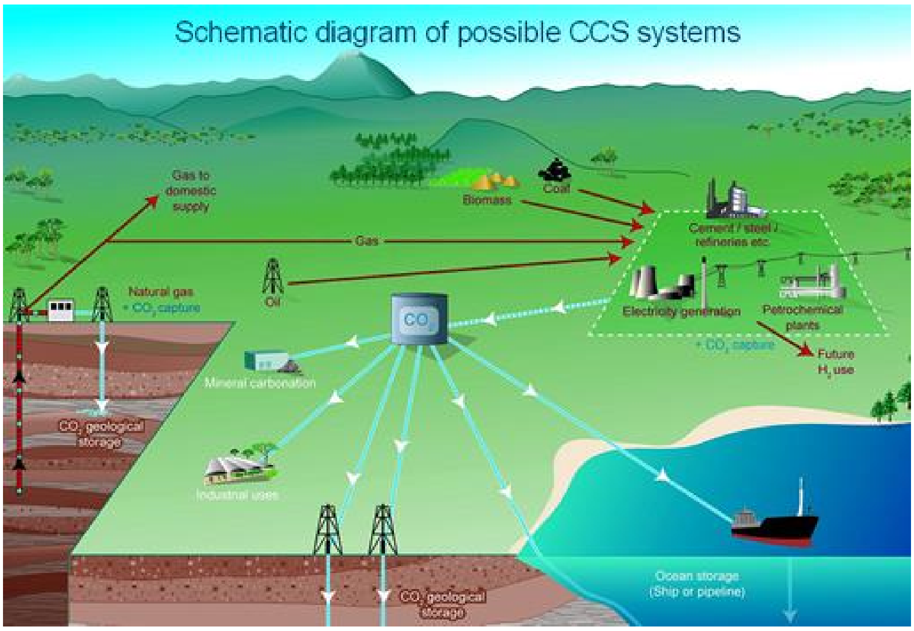


Figure 28: Schematic diagram of possible CCS systems, taken from [18]

In this research, only capture from large point sources will be taken into account, while small-scale capture and CO_2 capture from ambient air are not discussed, since current technologies don’t allow adequate results for these last two options. These include fossil fuel power plants (largest source of CO_2 emissions), fuel processing plants (e.g. for oil refining and for natural gas sweetening), and other industrial processes (like manufacture of iron, steel, cement, glass and bulk chemicals), which compose the previously introduced hard-to-abate industries. Capture of CO_2 from power and industrial flue gas streams can be performed in three different ways: post-combustion capture, pre-combustion capture and oxy-fuel combustion capture [19] (reported in Figure 29, taken from [20]). Post-combustion capture involves chemical absorption or membranes (better for streams with low volumetric concentrations of CO_2) and generates highly pure CO_2. The pre-combustion capture is usually performed in integrated gasification combined cycle (IGCC) plants and has the advantages of generating a carbon-free fuel (H_2) that does not release sulfur dioxide, and bringing high CO_2 concentrations in the flue streams (benefit for capture). Lastly, oxy-combustion capture works as the post-combustion one, but it combusts the fuel with pure oxygen (no NO_x and SO_x), leading to higher CO_2 concentrations in the flue gas.

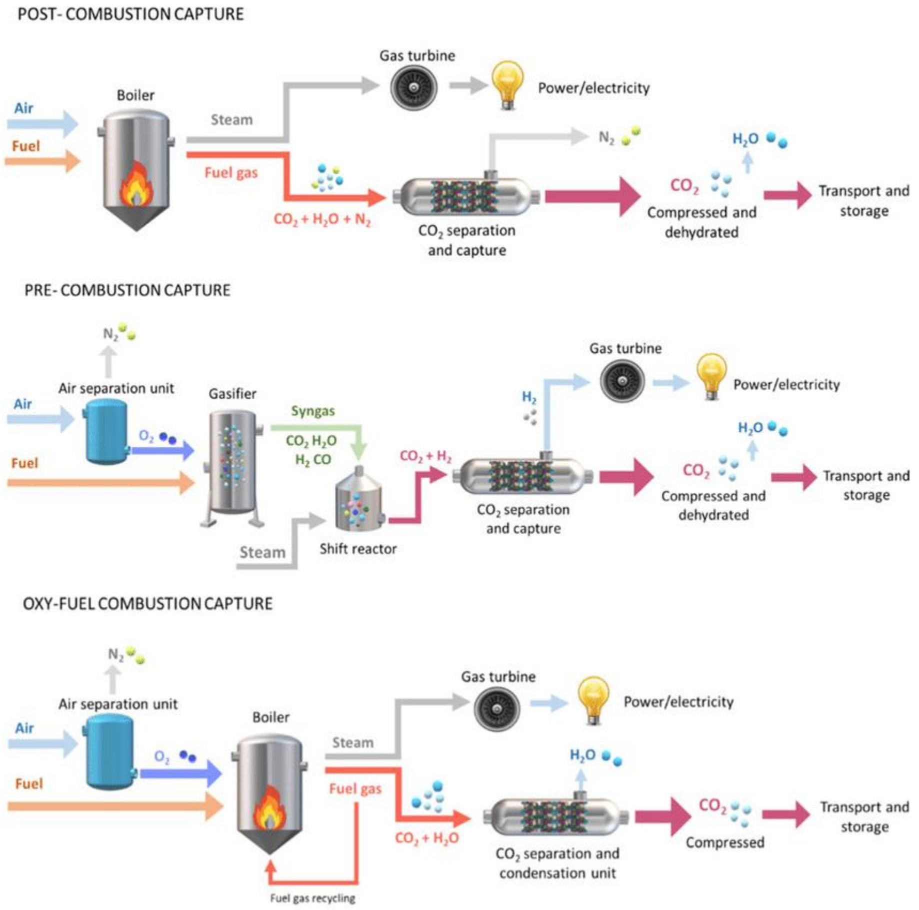


Figure 29: Structure of capture systems, taken from [20]

CO_2 is then transported with pipelines and/or ships to the specific storage site, where it is finally stored for a significant amount of time, allowing to use fossil fuels with low subsequent CO_2 emissions. To have a positive impact on climate change, the amount of storable CO_2 has to be comparable with the amount that is emitted by the economic sectors that were previously analyzed. Before analyzing the available volumes of underground storage it results useful to shortly describe this technique.

2.1 Technique’s description

Both carbon and CO_2 from biological and/or igneous activities and chemical reactions are naturally stored in the subsurface as coals, oil, gas, organic-rich shales, carbonate rocks and carbonate minerals, either in solution or in a gaseous or supercritical form, as pure CO_2 or as a gas mixture [21]. From these natural processes was developed the idea of injecting anthropogenic CO_2 into subsurface geological formations, as a mitigating strategy to reduce its concentration in the atmosphere, storing it away from it for geological times.

Before injection, CO_2 is compressed to the supercritical phase, in which it has the advantage of exhibiting a liquid-like density, that allows more efficient storing in the pores of sedimentary rocks. Injection is pursued by pumping the fluid into a well, typically at a depth at least higher than 1 km [21]. The fundamental characteristics for effective storage are porosity (to host CO_2), permeability (sufficient connection between the pores allows the injection of CO_2 at the required rate) and permeance (an upper caprock which guarantees containment).

2.1.1 Trapping mechanisms

The effectiveness of underground storage of CO_2 relies on different trapping mechanisms (reported in Figure 30, taken from [22]) that can be divided into physical and geochemical trapping.

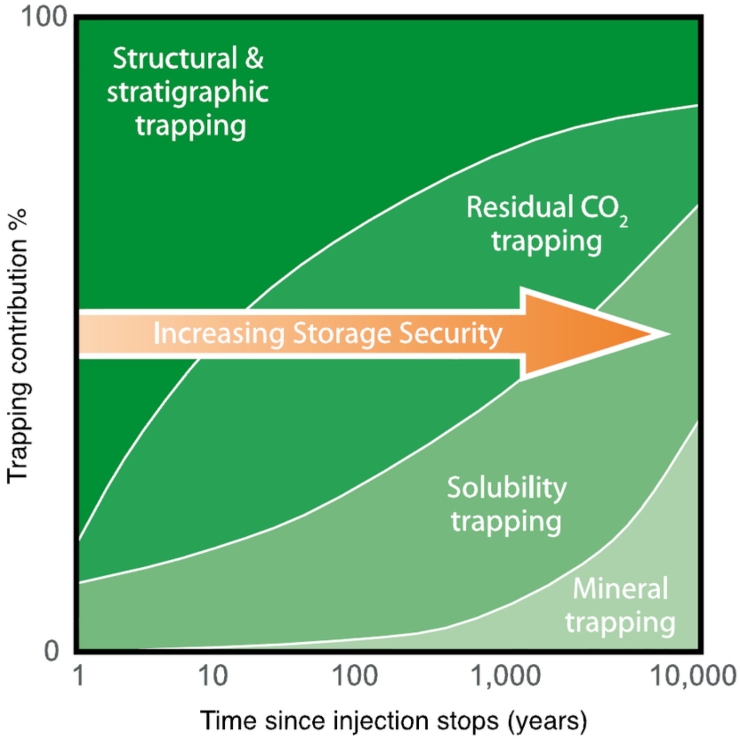


Figure 30: Effectiveness of trapping mechanisms, taken from [22]

Physical trapping is the main way to store CO_2 in geological formations and consists of immobilizing the fluid below low permeability seals (caprock) that are present in sedimentary basins, as traps that can either be structural (consisting of folded or fractured rocks) or stratigraphic (consisting of changes in rock type). In these types of trapping, close attention must be paid at not exceeding the permitted overpressure, to avoid fracturing the caprock or the risk of re-activating faults. Another type of physical trapping is the hydrodynamic one, which occurs in saline formations that do not present closed traps, where the rate at which the fluid migrates buoyantly upwards is slow enough to be considered as immobilized. In these formations when CO_2 reaches the top, it continues to travel horizontally as a different phase until it is trapped as residual CO_2 in the pores (Residual trapping).

Geochemical trapping instead consists of a series of geochemical interactions: the first step is the dissolution of CO_2 in the formation water (Solubility trapping), after which it is no longer a separated phase, eliminating the buoyant forces that push it upwards. The second step is the formation of ions as the rocks dissolve, this leads to further reactions and to the formation of stable carbonate minerals (Mineral trapping), that result as the most permanent form of geological storage. In Figure 31, which is taken from [23], all the various trapping mechanisms are graphically represented.

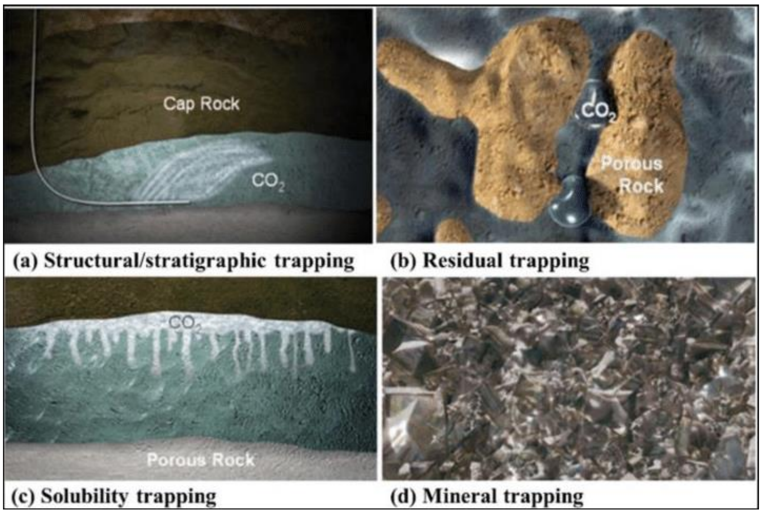


Figure 31: Trapping mechanism of CO_2, taken from [23]

2.1.2 Underground storage of CO_2 typologies

Underground storage of CO_2 can take place in different types of sedimentary basins (both onshore and offshore). The site must:

1. Provide sufficient capacity and injectivity;
2. Present a sealing caprock;
3. Be in a stable geological environment, in order not to compromise the integrity of the storage site itself.

It is possible to obtain scarce storage potential when dealing with basins that are either thin (≤1000 m), highly faulted and fractured, have undergone significant diagenesis, have over pressured reservoirs or have poor reservoir-seal relationships. There are many possible sites that fulfil these requirements (reported in Figure 32, taken from [24]), and depleted oil and gas reservoirs, together with saline formations, represent the best candidates.

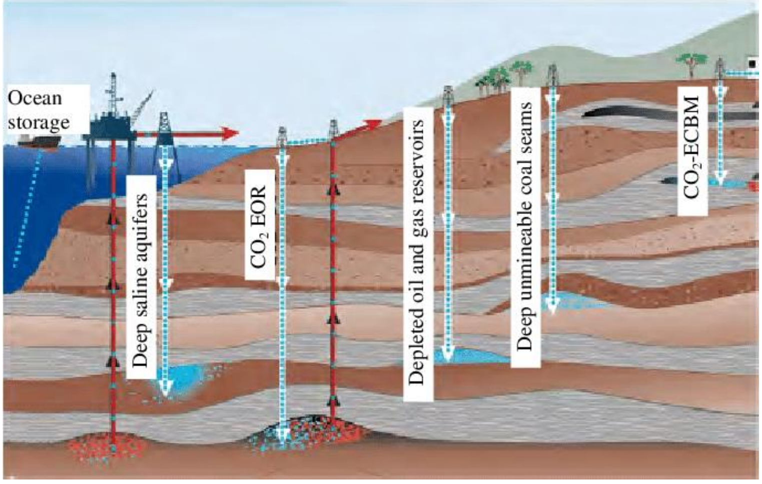


Figure 32: Possible injection sites, taken from [24]

Depleted oil and gas reservoirs represent significant options, since they already contained hydrocarbons before, providing integrity and safety. For this same reason, they also present the advantages of being already studied and modeled to predict possible developments and movements of trapped hydrocarbons. Moreover, in some cases the wells and equipment already in place can also be used for injection (and if the field is still producing hydrocarbons, there is also the possibility of implementing enhanced oil or gas recovery).

Also saline formations (deep sedimentary rocks saturated with formation waters or brines, containing high concentrations of dissolved salts) have large opportunities for CO_2 storage, as demonstrated by actual practice examples, like The Sleipner Project in the North Sea (Figure 33, taken from [25]), that is the world's first commercial CO_2 storage project, with a saline formation presenting a significant storage capacity [26].

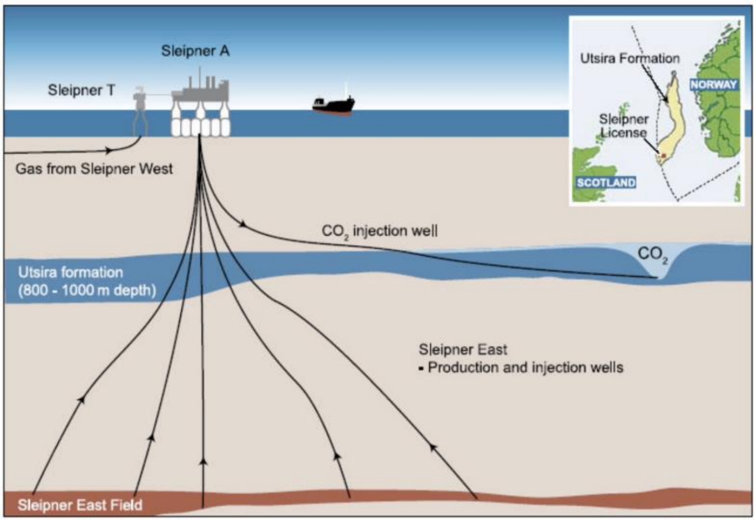


Figure 33: The Sleipner Project in the North Sea, taken from [25]

Other possible options are for example coal seams, where CO_2 can diffuse into the coal matrix and then get adsorbed into its micropores' surface. This typology of underground storage is possible in coal seams that were never mined or depressurized, and that can provide storage for geological times. Lastly, other geological media and/or structures that can be considered for geological storage of CO_2 include basalts, oil or gas shales, salt caverns and abandoned mines.

There are already ongoing projects of CO_2 storage (Figure 34, taken from the CO_2 Storage Resource Catalogue [27]), but for this technology to make an actual positive impact on CO_2 emissions' mitigation, many more structures must be developed.

Figure 34: Ongoing projects of CO_2 storage, taken from the CO_2 Storage Resource Catalogue [27]

In this context, it is also important to have a clear database showing where it is possible to store CO_2, to provide a match between the sources of emissions and the site where they will be stored, to improve economic, environmental and technical outcomes.

2.2 Underground storage capacity estimates

Nowadays, databases of underground storage capacity are very limited and/or inconsistent and incomplete. Most of the studies on this topic are developed at a regional scale, with the aim of achieving local capacity measurements. In fact, in the literature, detailed analysis of regional storage capacity for the main emitting regions are available, like China, Europe, the United States and Japan, but all these researches use different approaches and methodologies, with varying levels of detail, leading to incomparability between the data. Moreover, even if these areas result as the highest CO_2 emitters, these does not involve that there is no need to investigate also on the underground storage capacity of all the other countries.

The usual way to estimate regional storage capacity is the volumetric method, which firstly evaluates the available volume of pore space (product of the sedimentary area, thickness, and porosity), and then calculates the part of this volume that can actually be used for CO_2 storage, considering many factors. These factors can be of different nature: technical, like the processes of subsurface fluid injection, migration or stability in the long term, economic and regulatory limitations.

With this method, the equation is the product between the volume of pore space V, the density of CO_2 at subsurface p and T $\rho(\mathrm{P},\mathrm{T})$ and a storage efficiency factor E, as reported below [28]:

$$Storage\ Capacity = V * \rho(\mathrm{P},\mathrm{T}) * \mathrm{E}$$

The discrepancies in the various research are due to the assumptions and hypothesis that are made for the efficiency E and for the starting available pore volume that is considered.

In this research, to overcome these problematics, the values of CO_2 underground storage capacity in the different areas of the world are taken from a single study: "Developing a Consistent Database for Regional Geologic CO_2 Storage Capacity Worldwide" of the MIT Joint Program on the Science and Policy of Global Change [28], obtained using MIT's Integrated Global System Model.

2.2.1 Methodology

The MIT study aims at creating a consistent global database of geologic storage capacity, also comprehending regional values, which can be used to evaluate the potential of CCS. The procedure for estimating geological storage capacity that is used is based on the formation area method, suggested by the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG).

This is a simple methodology based on the assumption that favorable geologic conditions for CO_2 storage are considered as randomly allocated over sufficiently large areas. As only input it requires the area covered by sedimentary basins, assuming an average thickness of 100 meters and that half of it is covered by a seal. A storage efficiency factor is then applied to the resulting volume, leading average values to range between 0.1 and 1 million tons of CO_2/km^2 of storage capacity, with both a lower and a higher bound. The lower value is obtained assuming a closed system in which the pressure can't be dissipated, while the higher one considers an open system, in which pressure can be dissipated. Even if it is based on a very simple process, this method results to be in agreement with more detailed regional assessments.

In the MIT's study, this procedure has been slightly modified to consider also the formation thickness, since it has already been characterized globally, therefore it is not trivial to comprehend it in the evaluations. With this aim, the average sediment thickness is evaluated or extrapolated for each basin, and then the sum of formation volumes in various regions of interest is calculated.

A proportionality between the sedimentary formation volume and storage capacity is assumed and taken into account through a proper coefficient (analogous to the storage efficiency factor of the volumetric method, though they result incomparable as they are obtained from different starting volumes), for which two options were selected.

The first one accounts at best for local geology and various trapping mechanisms (identified as a best practice in capacity estimation methodologies by a IEA workshop) and represents the upper estimate of storage capacity; it is taken from the United States Geological Survey (USGS) assessment of $0.26*10^{-3}$ Gt of CO_2/km^3 of sedimentary basin. The second one also considers pressure increases and the relative impact on injection rate (neglected by the first one), therefore it is based on more restrictive assumptions (used on a study by Szulczewski), and it represents the lower estimate of storage capacity. The MIT's methodology then applies these two coefficients to the calculated sedimentary volumes, obtaining upper and lower estimates for each region.

2.2.2 Results

The upper and lower estimates of underground storage capacity of CO_2 for each region are reported below in Table 7:

Table 7: Upper and lower estimates of CO_2 underground storage capacity, taken from the MIT Database

Region	Estimated Storage Capacity [Gt]							
	Lower Estimate				Upper Estimate			
	Onshore	Offshore		Total	Onshore	Offshore		Total
		Technical	Practical			Technical	Practical	
Africa	1344	880	220	1563	9444	6185	1543	10986
Australia & New Zealand	334	699	261	595	2349	4912	1835	4184
Dynamic Asia	36	115	83	119	251	806	583	834
Brazil	224	267	73	297	1572	1877	515	2087
Canada	206	514	112	318	1445	3610	790	2236
China	325	100	77	403	2286	704	544	2830
Europe (EU+)	161	492	141	302	1129	3459	991	2120
Indonesia	96	166	67	163	672	1163	472	1144
India	75	264	25	99	525	1853	172	697
Japan	4	24	5	8	26	171	34	59
Korea	0	9	3	3	0	62	24	24
Other Latin America	443	614	163	606	3111	4317	1145	4257
Middle East	370	218	121	492	2603	1530	851	3454
Mexico	79	200	58	138	556	1408	411	967
Other East Asia	161	377	110	272	1135	2651	776	1911
Other Eurasia	415	202	70	485	2916	1422	494	3410
Russia	1180	621	54	1234	8291	4361	382	8673
United States	551	445	261	812	3872	3130	1836	5708
Global	6003	6208	1907	7910	42181	43622	13399	55581

The outcomes of this methodology results to be in agreement with estimates obtained from more detailed capacity assessments developed in specific regions (for example in The North Sea and also in the United States). However, it would be important to have further knowledge on both regional and global assessments of underground storage capacity, with the possibility of performing comparison between different studies. For offshore areas, an important part of the capacity is considered practically inaccessible, based on three basic criteria (considered as the most difficult to overcome): water depth exceed 300 meters, site is more than 200 miles off shore, and/or site is in the Arctic or Antarctic areas. These reductions impacted greatly the capacity in regions like Africa and Japan for water depth, due to steep continental shelfs, and also in Canada and Russia due to Arctic areas.

It is possible to see a significant difference between the lower and upper estimates, that indicate a global value of practically accessible underground storage capacity for CO_2 of respectively 8000 Gt and 56000 Gt. All the single regions as well present high discrepancies between the two estimates, with peaks in regions like Africa, Russia and the United States, and lower differences in smaller regions like Korea and Japan. However, in each case (except these last two) the difference is always of at least 500 Gt, therefore it is very impacting in terms of mitigating capacity.

These values are estimated accounting for current technologies, so it can also be possible to increase the practically accessible portion of the underground storage capacity within this century. Moreover, the storage capacity is assumed to be homogeneously distributed inside the different regions, which could be an unrealistic scenario for extended ones (for example Africa or the United States).

In Figure 35, Figure 36 and Figure 37 are reported the values of estimated onshore, offshore and total CO_2 storage capacity for the various regions.

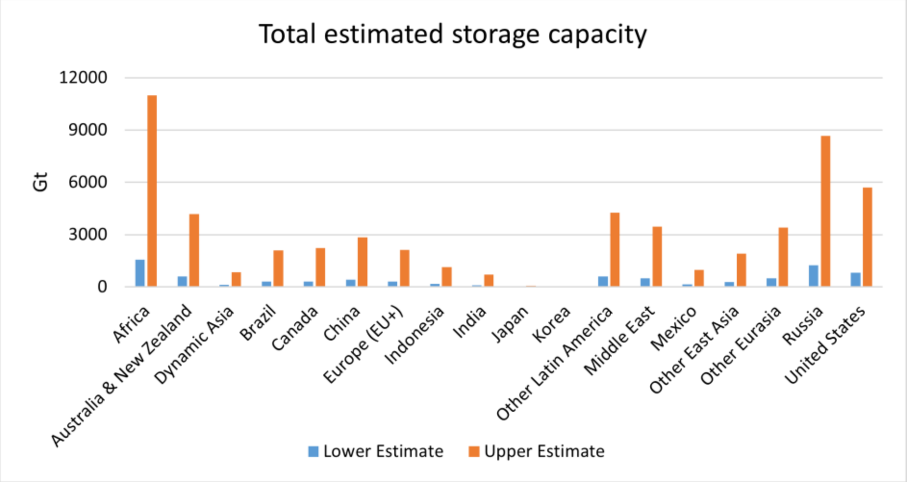


Figure 35: Total esimated underground CO_2 storage capacity, taken from the MIT Database

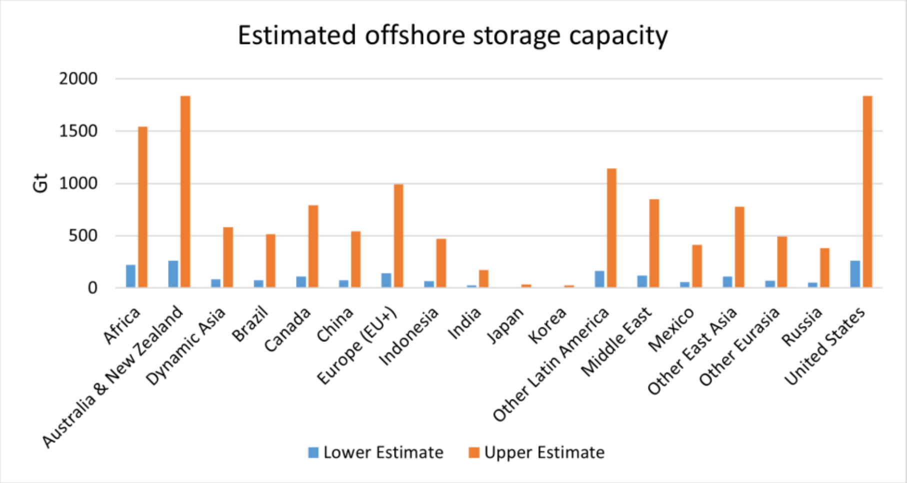


Figure 36: Offshore esimated underground CO_2 storage capacity, taken from the MIT Database

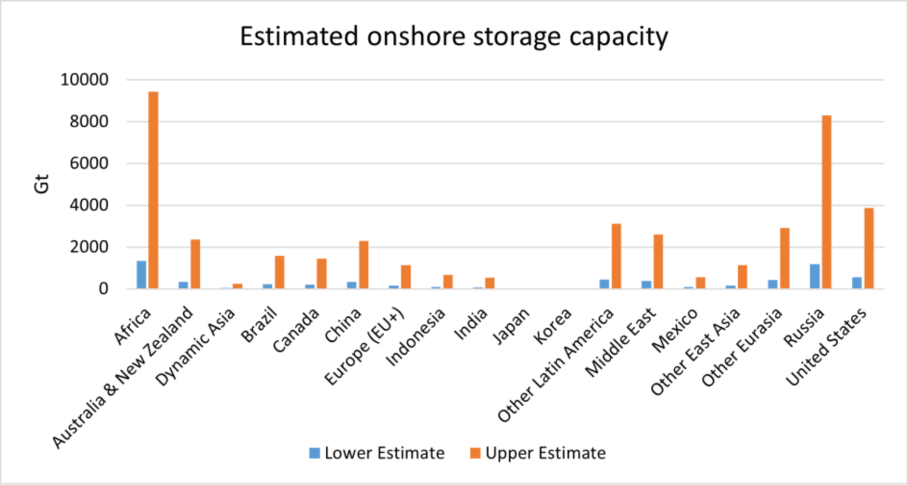


Figure 37: Onshore esimated underground CO_2 storage capacity, taken from the MIT Database

From these charts it is again possible to notice the large differences between lower and upper estimates. Moreover it's noticeable that, in most cases the highest contribute is given by the onshore capacity.

Lastly, to further compare these data with the ones on future CO_2 emissions, estimated in the previous chapter, it is necessary to assemble them in the five macro regions defined by the SSP Public Database [17], that are reported in Table 8.

Table 8: Countries composing the evaluated five marco regions

Region	Code	Countries
OECD 90 and EU member states and candidates	OECD	Albania, Australia, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Guam, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Montenegro, Netherlands, New Zealand, Norway, Poland, Portugal, Puerto Rico, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, The former Yugoslav Republic of Macedonia, Turkey, United Kingdom, United States of America
Reforming Economies of Eastern Europe and the Former Soviet Union	REF	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
Asian countries with the exception of the Middle East, Japan and Former Soviet Union states	ASIA	Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China, Democratic People's Republic of Korea, Fiji, French Polynesia, India, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Micronesia, Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papua New Guinea, Philippines, Republic of Korea, Samoa, Singapore, Solomon Islands, Sri Lanka, Taiwan, Thailand, Timor-Leste, Vanuatu, Vietnam
Middle East and Africa	MAF	Algeria, Angola, Bahrain, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte d`Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Nigeria, Occupied Palestinian Territory, Oman, Qatar, Rwanda, Réunion, Saudi Arabia, Senegal, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Swaziland, Syrian Arab Republic, Togo, Tunisia, Uganda, United Arab Emirates, United Republic of Tanzania, Western Sahara, Yemen, Zambia, Zimbabwe
Latin America and the Caribbean	LAM	Argentina, Aruba, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, United States Virgin Islands, Uruguay, Venezuela

The numerical values of the different components of the lower and upper estimates of storage capacity for these macro regions are summarized in Table 9.

Table 9: Estimated storage capacity in the five macro regions

Region	Estimated Storage Capacity in the five chosen regions [Gt]					
	Lower Estimate			Upper Estimate		
	Onshore	Offshore	Total	Onshore	Offshore	Total
REF	1595	124	1719	11207	876	12083
ASIA	693	365	1059	4869	2571	7440
MAF	1714	341	2055	12047	2394	14440
LAM	746	294	1041	5239	2071	7311
OECD	1256	780	2035	8821	5486	14307

In Figure 38 is reported the global visualization.

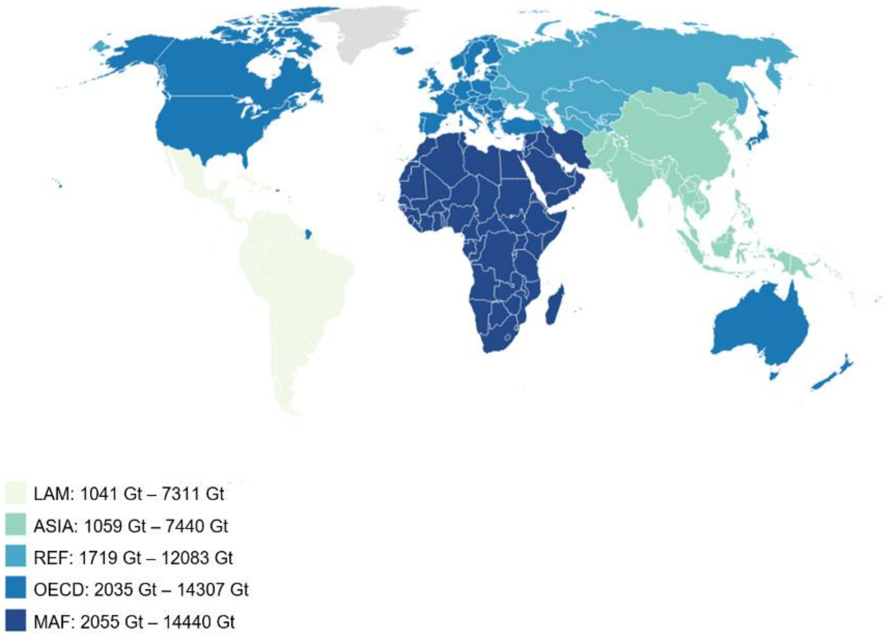


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Figure 38: Map reporting the lower and upper estimates of storage capacity in the five macro regions

3. Future emissions and storage capacity comparisons

In the previous chapters the estimates of future CO_2 emissions in the different SSP scenarios, and the underground storage capacity in the various regions of the world were reported. Since underground storage of CO_2 could represent an important opportunity for mitigating climate change, it is useful to compare these values.

In this section, only the lower estimates of underground storage capacity will be considered, in order to adopt a procedure as cautionary and realistic as possible. For what concerns future CO_2 emissions, IPPC does not define the likelihood of the scenarios, however the 2020 report "Emissions – the 'business as usual' story is misleading" by Z. Hausfather et al. [29], defined SSP-8.5 as highly unlikely, SSP3–7.0 as unlikely, and SSP2–4.5 as likely (as shown in Figure 39).

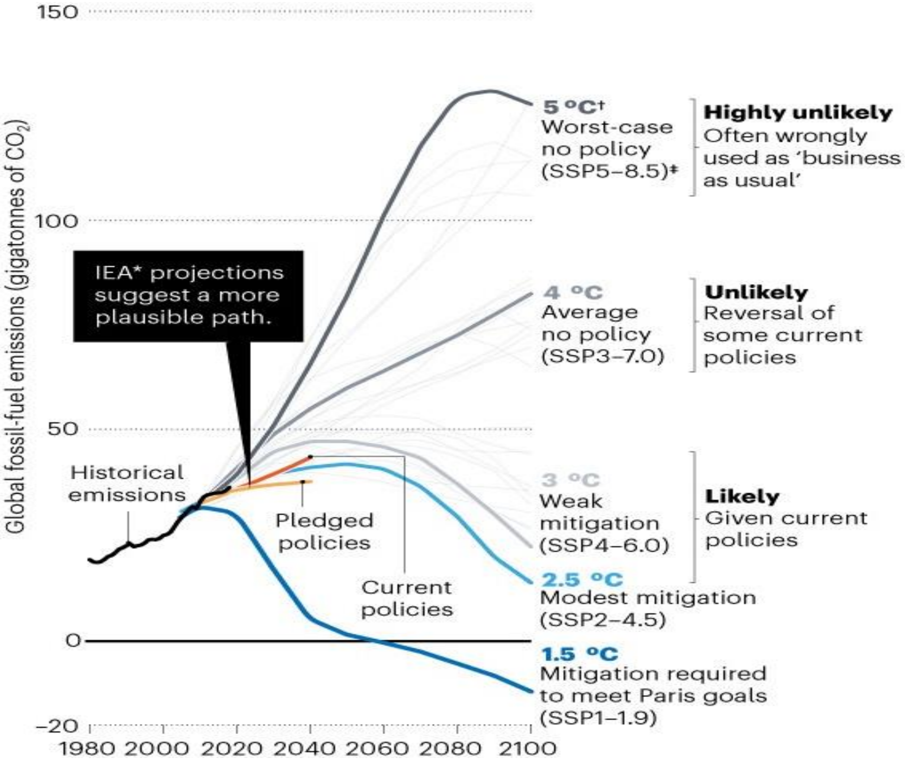


Figure 39: Likelihood of the various SSP scenarios

For this reason, to be compliant with the intent of following a cautionary and realistic procedure, in this section, only values obtained from the SSP3-7.0 (being the first unlikely scenario, if the underground storage is enough for its data, it will surely be also for the more realistic ones) will be displayed and compared with the ones of underground storage, since accounting for lower ones like SSP2-4.5, could lead to underestimations.

As previously mentioned, the focus is on the hard to abate industries' emissions for the upcoming 2030 and 2050 Net Zero Targets, and at a global scale the future CO_2 emissions of these impacting sectors are reported in Table 10, this time in Gt, to visualize them with the same unit of measure that is used for the underground storage data.

Table 10: Future global CO_2 emissions of the most impacting economic sectors, from the SSP Public Database

Future global emissions (SSP3-7.0) [Gt]		
	2030	2050
Energy Sector	22,8	31,5
Industrial Sector	11,6	12,7
Total value	34,4	44,1
Cumulative value	308,1	1046,2

For this comparison, the values of interest are the cumulative ones (evaluated by summing the values of future emissions, hypothesizing to start the injection in 2020). At a global scale, cumulative expected emissions for 2030 and 2050 (308,1 Gt and 1046,2 Gt) result to be way lower than the total underground storage capacity that was estimated in the previous chapter (globally 7910 Gt), highlighting the strong opportunity offered by this technology. However, this type of comparison results to be incomplete, since in the context of CCS it is very important to have a match between the source of emissions and the storage site, to provide both economic and technical feasibility of the process.

For this reasons, the subdivision in five different macro regions and the analysis of the highest emitting countries were proposed in the other chapters, in order to verify the opportunity for each one of them to store its emissions within its boundaries.

3.1 Regional analysis

In Table 11 are reported the cumulative values of CO_2 emissions of the five macro regions, and their respective underground storage capacities.

Table 11: Cumulative future CO_2 emissions of the five macro regions

Cumulative CO_2 emissions [Gt]			Storage capacity [Gt]
Region	2030	2050	
ASIA	164,7	566,5	1059
LAM	13,6	47,2	1041
MAF	29,1	109,1	2055
OECD	78,7	250,7	2035
REF	22,0	72,7	1719

It is noticeable that the available volumes are, in all five cases, high enough to host all the CO_2 that will be emitted until 2030 and 2050, allowing to reach the Net Zero Targets. This results particularly true for Middle East and Africa, that present the highest value of storage capacity and very low estimates of future emissions, due to low industrialization with respect to the other regions. As visible in Figure 40, the storage capacity is more than enough to cover the emissions the are expected for the whole century, without even filling half of the available storage volume.

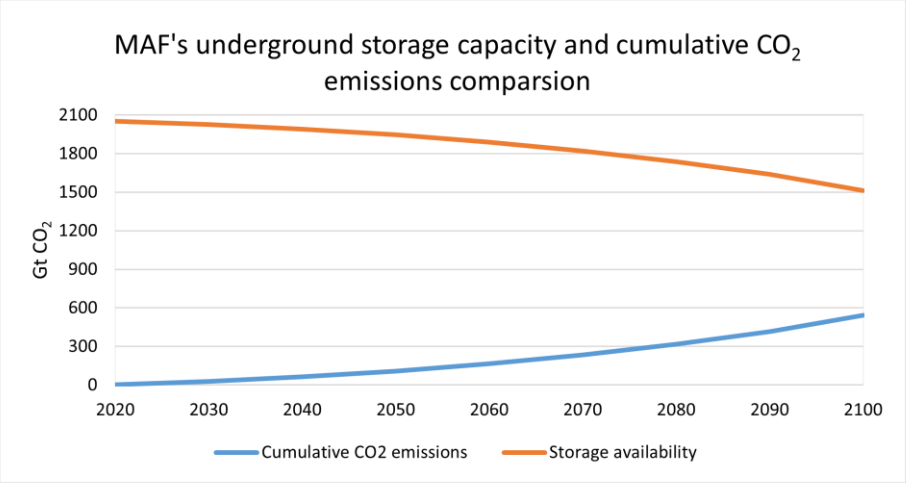


Figure 40: MAF's future cumulative CO_2 emissions and underground storage capacity availability

Moreover, in REF and LAM (as reported in Figure 41), even if the storage capacity is not as high as the previous one, the estimated future emissions result to have way lower values than this one. For this reason, also in these macro regions there is enough availability to store all the emissions that are expected for the whole century.

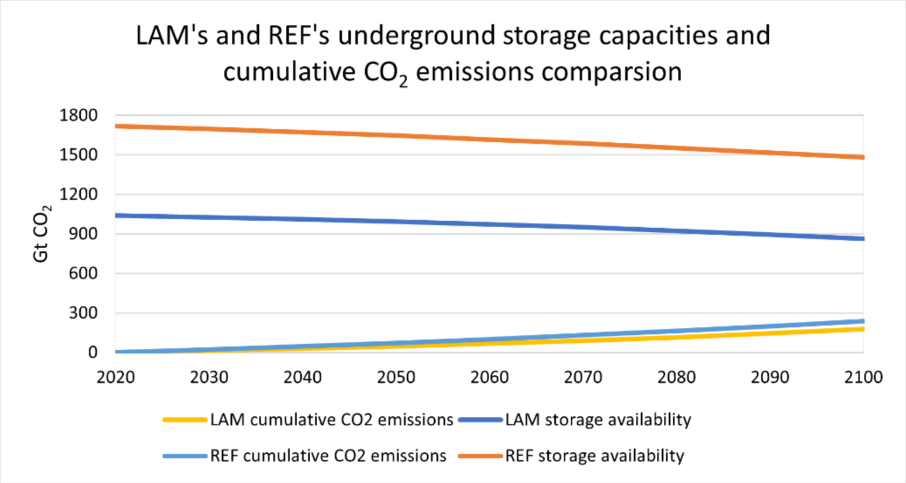


Figure 41: Lam's and REF's future cumulative CO_2 emissions and underground storage capacity availability

Lastly, it is important to focus on both OECD and ASIA, being the regions with highest emissions.

The first ones are developed countries that have the potential to give important contributes in mitigating climate change, thank to high technological advances and a very high value of underground storage capacity (as visible in Figure 42).

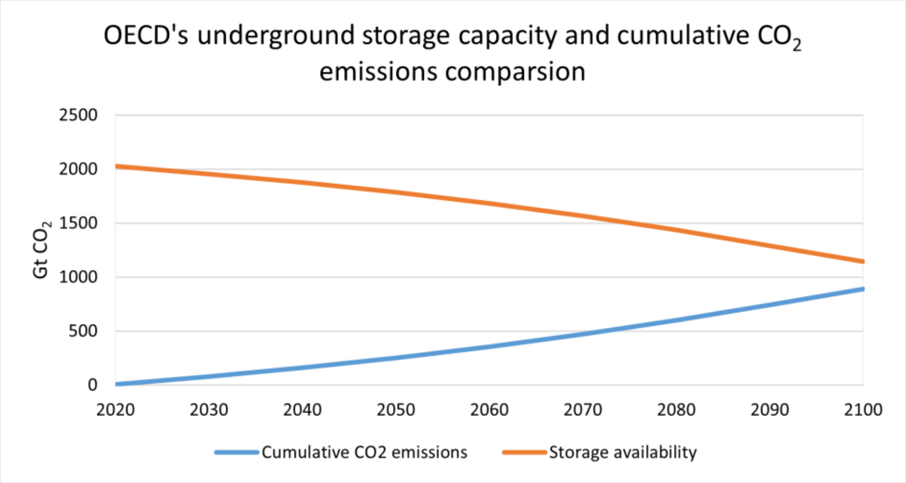


Figure 42: OECD's future cumulative CO_2 emissions and underground storage capacity availability

In these countries, it would be very important to exploit the possibility of underground storage of CO_2 to mitigate the emissions coming from the hard to abate industries. For example, in the United States the capacity of storage is one of the highest for a single country (as visible in Figure 43) and, even if it is the third largest CO_2 emitter of the world, its value results sufficiently high to store all the emissions expected by the US in this century.

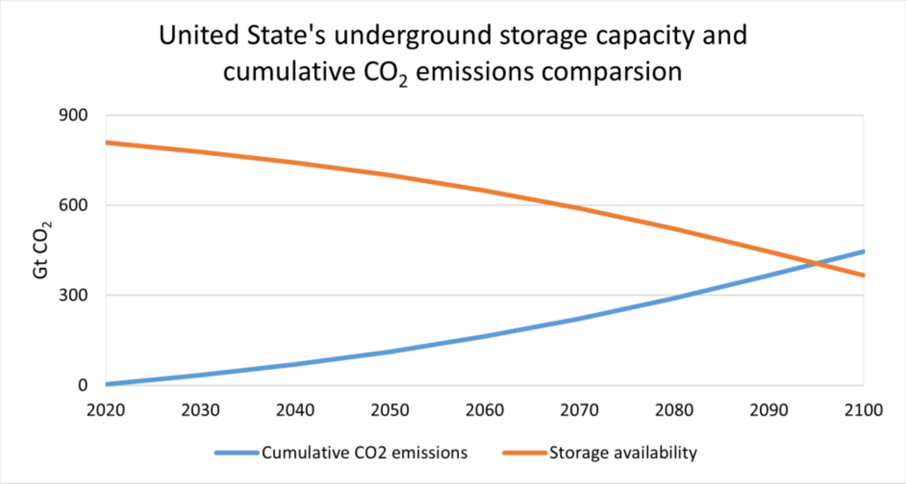


Figure 43: United States's future cumulative CO_2 emissions and underground storage capacity availability

Lastly, ASIA resulted as the highest emitting macro region, with countries like China, and India that have the most significant impacts on global emissions, and not always the possibility of mitigating them inside their own boundaries. In fact, as visible in Figure 44, this region results to only have enough space to store emissions until 2070, mainly due to these two countries, that both have low storage capacities with respect to the magnitude of their future estimated emissions (only able to store them until 2050), as visible in Figure 45, affecting also the availability for the other countries in Asia.

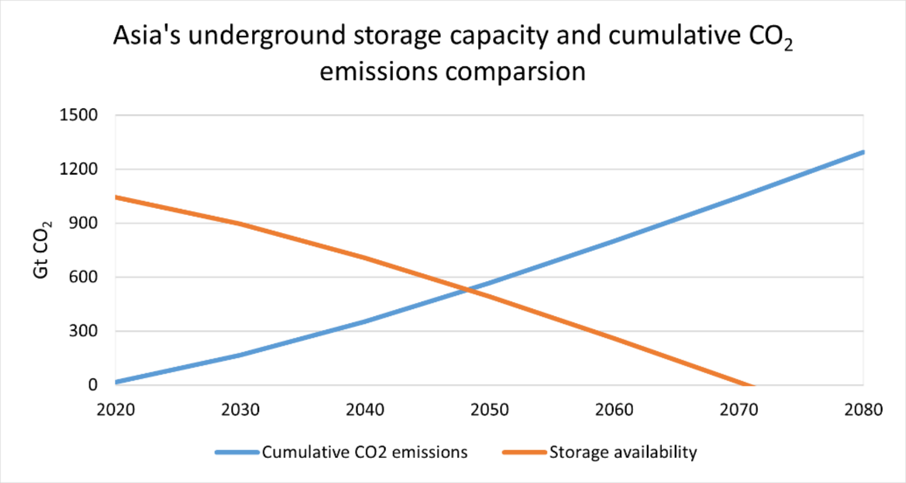


Figure 44: ASIA's future cumulative CO_2 emissions and underground storage capacity availability

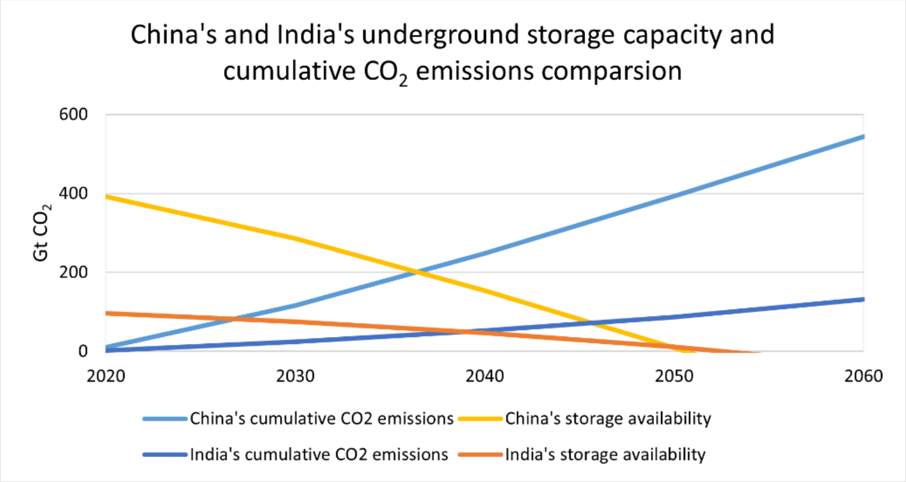


Figure 45: China's and India"s future cumulative CO_2 emissions and underground storage capacity availability

3.2 Deployment analysis

To have a complete overview of CCS systems, after demonstrating its high mitigating potential, also costs and the level of maturity of the technology have now to be considered, to deduce whether these systems have the potential to bring benefits for the firms that employ it, instead of just only expenses.

Quantifying and understanding the financial outlays and economic implications of CCS, furnishes stakeholders, policymakers, industries, and investors with a robust foundation upon which it is possible to make informed choices on the strategic deployment of CCS technologies, while also accounting for the economic sustainability of these activities. The literature provides different analyses of this topic, and in this paragraph a critical review of these sources will be performed, in order to report realistic ranges of costs for the different stages of CCS technologies.

This economic evaluation results to be a complex techno-economic endeavor, that needs to take into account numerous variables and scenarios. In fact CCS's costs depend on many factors, like the process typology, the capture system that is implemented, the transport's media and the storage site position. First of all, different capture technologies each exhibits distinct capital and operational costs and requirements. Following the capture stage, cost considerations extend to the transportation and injection of captured CO_2 into suitable geological formations for storage. At each phase, financial implications intertwine with geological, technological, and regulatory aspects, further compounding the methodological complexity. Between the factors that affect the entity of the costs are: nature and scale of the emission source, scale of the capture technology, geological characteristics of potential storage sites and their distance from emission sources, and the associated geological preparation that is required. Additionally, the regulatory environment and prevailing economic conditions, including carbon pricing mechanisms and government incentives, are variables that require rigorous evaluation for a comprehensive cost assessment.

3.2.1 Maturity of the technology

When evaluating the costs of a technology, it is also important to consider the level of development that it has reached, to move towards more efficient ones, with lower overall costs in all parts of its value chain. In fact, in a cost analysis, when the technology is still under development, therefore not mature yet, the costs are based on estimates made by comparing the systems to other similar recent technologies. For this reason, these are considered as FOAK (First Of A Kind) projects, in which the costs are not the same as the ones of NOAK (Nth Of A Kind) projects, meaning that reductions should be registered with technological development (the Global CCS Institute estimates it around 3.4% – 8.1% in the power sector, and 9.3% for the industrial one). The 2021 report “Technology readiness and cost of CCS” published by the Global CCS Institute [33], highlights that CCS is going through the pattern of performance improvements and costs reduction that new industrial technologies experience with increased deployment, as for example demonstrated by the reduction of around 50% of the cost of capture in coal fired power plants registered in the past 10 – 15 years.

For this reason, it is useful to also analyze the level of maturity of CCS, to better understand at which stage of its deployment it currently is. For this evaluation the Technology Readiness Level is introduced, which is a qualitative metric used to assess the maturity of a technology with a scale going from 1 to 9: 1,2,3 are research states, 4,5,6 are development states, and 7,8,9 are demonstration states. In the 2021 report “Technology readiness and cost of CCS” published by the Global CCS Institute, the TRL is evaluated for all the CCS technologies. The outcomes of this analysis highlights that CCS spans the full 1 to 9 range, depending on the step that is considered. Capture technologies result to have overall low TRLs, mainly because historically they have been applied to gas streams with high concentrations, while for CCS applications they need to be efficient also on low-concentration ones, like the dilute gas streams in power generation and other industries. Moreover, the transportation section of CCS results to have generally high TRLs (9), regardless of the method (pipelines, ships, truck and rail). Although this section presents positive results, there is still the need to develop larger scale ships or rail transportation’s systems for CCS, since currently only pipelines are able to provide significant transportation in this context. For shipping, the technology ranges all the TRL scale, due to reduced experience in the context of CO_2 transport; however, it should result feasible, as it has been in the gas industry for almost a century now, for various pressurized gases. The same reasoning can be made for shipping, since CO_2 transport by this media and the relative infrastructure should be almost the same as the one exploited for LNG (Liquified Natural Gas) and LPG (Liquified Petroleum Gas). Lastly, for what concerns the storage section, there are mainly three different mature technologies: CO_2-enhanced oil recovery (TRL of 9) that has been performed for almost 50 years, storage in saline formations (TRL of 9) that has been first performed in 1996 in the North Sea, and storage in depleted oil and gas fields (TRL from 5 to 8), that is technically mature but only has few demonstration projects.

3.2.2 Costs of CCS

For what concerns the actual costs, the 2018 report "An assessment of CCS costs, barriers and potential" by S. Budinis et al. [30] identifies costs of CCS as the main factor that is withholding this technology from spreading at a large scale, also due to the complexity of properly assessing them, ascribed to the lack of empirical data. In this research, costs are reported in \$2015, to also consider the effects of inflation.

To evaluate the costs of CCS for a firm, the concept of energy (or efficiency) penalty is introduced: the performance comparison of a plant with or without CCS. Energy penalty is applied to power generation plants, while efficiency penalty is applied to industrial ones (can also be applied to the power sector), the first one returns the proportional loss in power output, and the second one the decrease in efficiency. These metrics are evaluated as:

$$Energy\ penalty = 100 * \left(\frac{Power\ output\ without\ CCS - Power\ output\ with\ CCS}{Power\ output\ without\ CCS}\right)$$

$$Efficiency\ penalty = Efficiency\ without\ CCS\ (\%) - Efficiency\ with\ CCS\ (\%)$$

For the power sector, also the Levelized Cost Of Electricity (LCOE) is employed (\$/MWh). Moreover, to evaluate the cost of CCS per ton of CO_2 sequestered (\$/tCO_2), it is possible to use metrics like the avoided, captured or abated CO_2:

$$Cost\ of\ avoided\ CO_2 = \frac{(COE)_{CCS} - (COE)_{ref}}{(tCO_2/MWh)_{ref} - (tCO_2/MWh)_{CCS}}$$

$$Cost\ of\ captured\ CO_2 = \frac{(COE)_{CC} - (COE)_{ref}}{(tCO_2/MWh)_{captured}}$$

$$Cost\ of\ abated\ CO_2 = \frac{(NPV)_{low-C} - (NPV)_{ref}}{(tCO_2)_{ref} - (tCO_2)_{low-C}}$$

COE is the cost of electricity generation in \$/MWh and NPV is the Net Present Value of the evaluated scenario. "CCS", "ref" and "cc" refer to plants with CCS, without CCS and only to the capture step. The Cost of Avoided CO_2 includes capture, transport and storage steps (it accounts for extra energy and emissions to operate the CCS), the

Cost of Captured CO_2 only considers capture (it disregards the extra emissions cause by the CCS itself), and the Cost of Abated CO_2 accounts for multiple emissions sources, resulting to be the best for IAMs, since it allows to perform comparisons between different energy systems. Moreover, the Cost of Avoided CO_2 is obtained by subtracting the increased CO_2 emissions observed in a firm with the CCS system from the total captured CO_2 (as visible in Figure 46), resulting as the best metric for evaluating the cost of CCS.

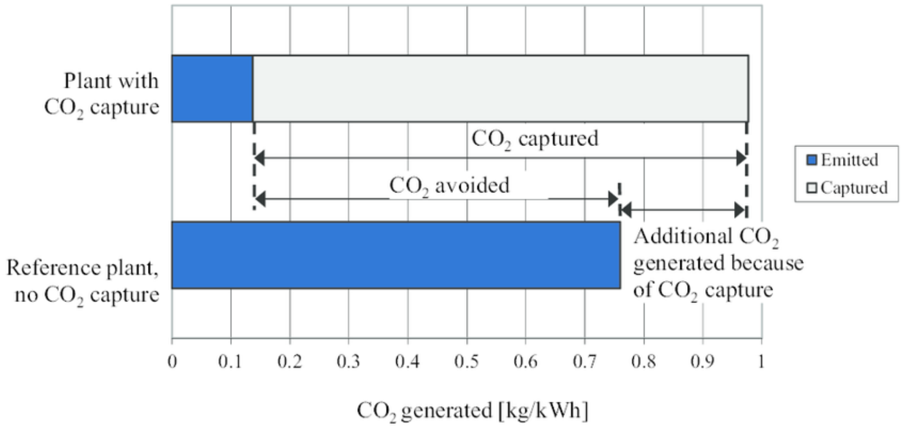
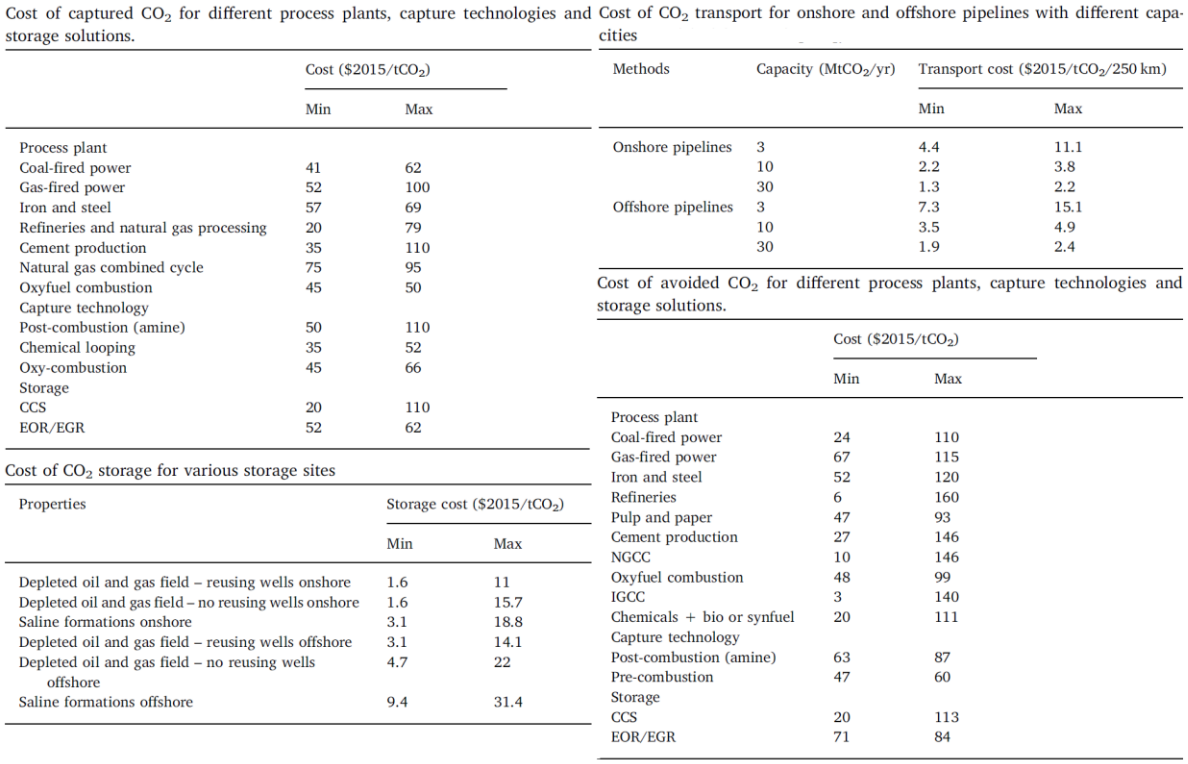


Figure 46: Example of plant's CO_2 emissions with and without CCS system

The study reports a table of cost of captured CO_2 considering various process plants, capture technologies and storage solutions, that range from 20 \$2015/tCO_2 , for refineries and natural gas processing, to 110 \$2015/tCO_2, for cement production [30]. Another table reports the costs of CO_2 transportation considering different pipeline capacities (MtCO_2/yr) and locations (onshore or offshore), that result to range from 1.3 \$2015/tCO_2/250km with a capacity of 30 MtCO_2/yr, to 15.1 \$2015/tCO_2/250km with a capacity of 3 MtCO_2/yr [30]. Moreover, also the costs of storage have been reported, considering different storage sites (depleted oil and gas fields or saline formations), locations (onshore or offshore) and the possibility to reuse already existing infrastructures: ranging from 1.6 \$2015/tCO_2 to 31.4 \$2015/tCO_2. Lastly, also a table reporting the cost of avoided CO_2 depending on process plant, capture technology and storage solution, has been reported in the study, in which it is possible to observe a large variability, depending on the typology of plant.

All the above mentioned tables from the study, are reported together in Figure 47, taken from [30].



Cost of captured CO_2 for different process plants, capture technologies and storage solutions.

	Cost ($2015/t$CO_2$)	
	Min	Max
Process plant		
Coal-fired power	41	62
Gas-fired power	52	100
Iron and steel	57	69
Refineries and natural gas processing	20	79
Cement production	35	110
Natural gas combined cycle	75	95
Oxyfuel combustion	45	50
Capture technology		
Post-combustion (amine)	50	110
Chemical looping	35	52
Oxy-combustion	45	66
Storage		
CCS	20	110
EOR/EGR	52	62

Cost of CO_2 storage for various storage sites

Properties	Storage cost ($2015/t$CO_2$)	
	Min	Max
Depleted oil and gas field – reusing wells onshore	1.6	11
Depleted oil and gas field – no reusing wells onshore	1.6	15.7
Saline formations onshore	3.1	18.8
Depleted oil and gas field – reusing wells offshore	3.1	14.1
Depleted oil and gas field – no reusing wells offshore	4.7	22
Saline formations offshore	9.4	31.4

Cost of CO_2 transport for onshore and offshore pipelines with different capacities

Methods	Capacity (MtCO_2/yr)	Transport cost ($2015/t$CO_2$/250 km)	
		Min	Max
Onshore pipelines	3	4.4	11.1
	10	2.2	3.8
	30	1.3	2.2
Offshore pipelines	3	7.3	15.1
	10	3.5	4.9
	30	1.9	2.4

Cost of avoided CO_2 for different process plants, capture technologies and storage solutions.

	Cost ($2015/t$CO_2$)	
	Min	Max
Process plant		
Coal-fired power	24	110
Gas-fired power	67	115
Iron and steel	52	120
Refineries	6	160
Pulp and paper	47	93
Cement production	27	146
NGCC	10	146
Oxyfuel combustion	48	99
IGCC	3	140
Chemicals + bio or synfuel	20	111
Capture technology		
Post-combustion (amine)	63	87
Pre-combustion	47	60
Storage		
CCS	20	113
EOR/EGR	71	84

Figure 47: Examples of CCS systems costs, taken from [30]

The total cost of CCS can be evaluated as the sum of the costs of the three different steps. The previously mentioned 2021 study “Technology readiness and cost of CCS” of the Global CCS Institute, analyzes more in detail the composition of these costs in the various steps of the CCS process. In general, the total cost of CCS results to be composed of the costs of: capture and purification of the gas up top 95% purity by volume, dehydration and compression/liquefaction for transportation, transportation itself, CO_2 injection and lastly, monitoring. Again, in this study the values are case-dependents, and the results (except the ones for capture) are reported in Figure 48, taken from the mentioned study.

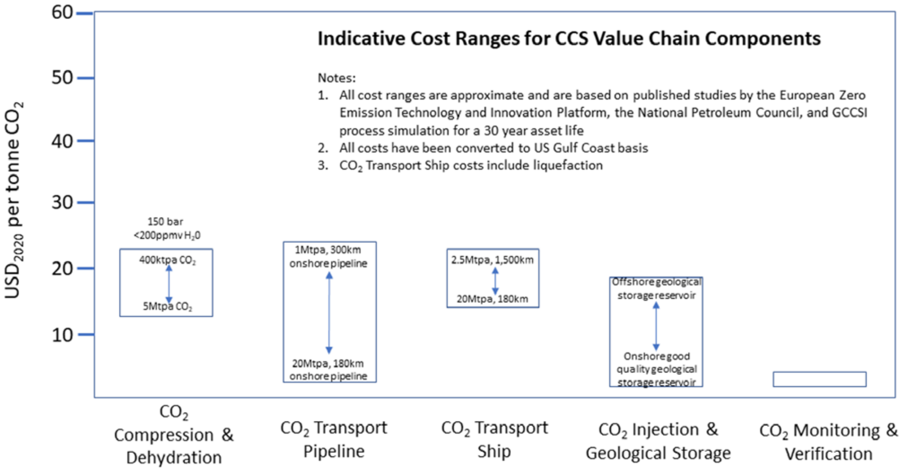


Figure 48: Costs of the different steps of CCS, takes from [33]

For what concerns capture, which accounts for the major costs in power generation and industrial plants, the main driving factors result: technology's maturity, properties of the source gas (costs are usually inversely proportional to the partial pressure of CO_2 in the gas stream, since it affects the size of the equipment, energy requirements and typology of the capture technology), and the scale of the plant (higher rates of production usually involves lower unit costs). The costs of capture in different industrial processes are reported in Figure 49, also taken from the mentioned study [33].

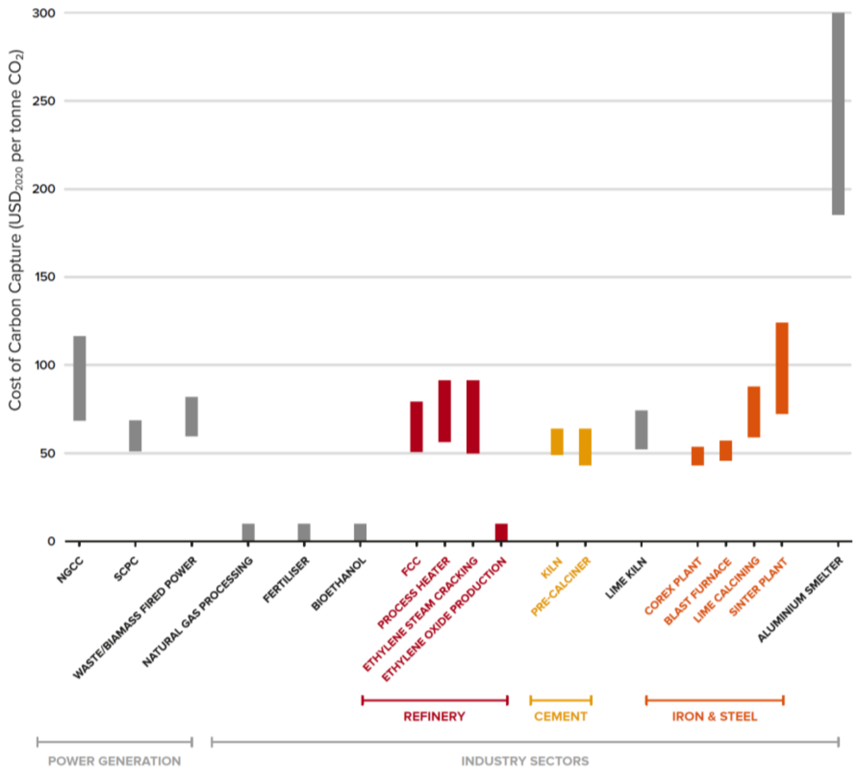


Figure 49: Costs of CO_2 capture in different industrial processes, taken from [33]

From these outcomes it is possible to define some practices to reduce capture's costs:

1. Capturing capacity should be of at least 0.4 – 0.45 Mtpa;
2. Utilization of modular carbon capture plants (built in standardized ways for mass production), which can reduce the plant capital costs;
3. Utilization of the heat coming from combined heat and power (CHP) plants in large industrial plants, such as steel, pulp and paper, and waste to energy, instead of building a new boiler specifically to provide steam for the capture, thus reducing the costs of energy;
4. Utilization of the heat coming from waste heat from the production processes in plants like the ones for cement, iron and steel production;

For what concerns transportation of large quantities CO_2, the gas must be dehydrated from water and then there are two possibilities: compression to dense phase for pipelines, and refrigeration to liquid phase for vehicles (ship, truck, etc..). The costs of these steps vary greatly depending on the media of transportation and on the distance that needs to be traveled, as seen in Figure 48. In general, it results that the costs of transportation decrease significantly as the capacity of the pipelines increases, and it is also greatly affected by the large amount of energy required for compression.

Lastly, for the storage step, costs are dependent on the characteristics of the geological storage site. In fact, for already studied and equipped sites (depleted oil and gas reservoirs), costs result lower; moreover also the location (onshore or offshore) and the distance from the capture facility have great impacts. Lastly, also the injectivity of the storage site is very important (costs are inversely proportional to this metric).

From these studies, it results that there is a large range of costs of CCS, offering the opportunity to obtain emissions' abatement at competitive costs. In this context, it is fundamental to accelerate the rate of deployment of CCS, also implementing supporting policies and incentivizing private investments.

Due to the previously mentioned high complexity of the CCS system, it results useful to enrich this analysis with another sources on the topic: the 2023 report "The Bottom Line: Why the Cost of Carbon Capture and Storage Remains Persistently High" by K. Sievert et al. [31] based on the Canadian case, estimates the costs of CO_2 capture in the range 27–48 CAD/tCO_2 for concentrated gas streams and 50–150 CAD/tCO_2 for diluted ones. The comparison is not so direct due to different currencies and inflation, however, in general the costs results compliant with the ones in the other studies.

This paper highlights the disparity of capture costs for different types of industrial applications, mainly between the ones with high CO_2 concentrations (like natural gas processing and ammonia production), and the ones with more diluted streams (like coal-fired power plants, steel, cement, and hydrogen production) and higher capture costs. This high disparity leads the authors to suggest that, unlike many other technologies, capture's costs for the second type of plants will probably not decline with higher investments and innovation, due to too complex requirements and the need for customization of this technology. The authors base this opinion on the comparison of the experience rate of CCS with the ones of other technologies (like solar PV and wind turbines), highlighting that, despite being in commercial use for over 50 years, CCS has experienced reductions in costs that results to be too low.

This outcome results to be in great contrast with the one of the Global CCS Institute, mentioned before. However, this study also highlights that CCS has a high potential for the hard to abate industries, which have complex processes (carbon-intensive and high-heat processes), that do not have efficient and cost-effective alternatives for decarbonization, electrification and emissions reductions.

3.3 Comments

From the comparisons reported above it is possible to state that, in terms of volumes, underground storage of CO_2 results feasible in all the different regions of the world, and more specifically, also in the highest emitting countries. However, not all the analyzed areas result to have the availability to store all the CO_2 that will be emitted in the near future (like China and India, or also Asia in general). For this reason it is important to optimize the use of this available volume. In fact, since the storage capacity cannot be infinite, just storing the emitted CO_2 would only postpone the problem of increasing concentrations of CO_2 in the atmosphere to when there will be no more space to store.

In this context, it is very important to consider the emitted (and then stored) CO_2 as a resource that can be reused in many applications, and consider CCS only as a temporary collection of this resource for further use, allowing the underground to never reach saturation. In this way it is possible to give value to the CO_2 that has been collected, providing benefits for both climate change mitigation and the hard to abate industries themselves, since instead of releasing CO_2 in an uncontrolled manner in the atmosphere, they are able to obtain a revenue by reusing it.

Moreover, from the costs analysis, it resulted that for the hard-to-abate industries, the deployment of CCS systems is necessary and feasible to achieve emissions' abatement. In this context, also policy initiatives and the creation of regulatory frameworks and financial incentives are needed to encourage industries to invest in CCS infrastructure. In fact, incentivizing investments in CCS not only encourages early adoption, but also contributes to technological advancements, thereby reducing costs over time.

However, it also resulted that the costs associated with CCS systems can be prohibitive for many other industries. This is where the concept of coupling CCS with carbon utilization, becomes necessary also in economic terms (in addition to the previous volumetric assessments). The coupling of CCS with CU not only mitigates economic challenges, but also opens up opportunities for revenue generation, emissions reduction and sustainable resources utilization, supporting the goal of achieving a sustainable and low-carbon future while addressing the challenge of hard-to-abate industries.

These are the basis on which the concept of CCUS (Carbon Capture Utilization and Storage) has been developed. As this results to be the best option to exploit the mitigating opportunities offered by underground storage of CO_2, the next chapter will explore more in detail this technologies (CCUS), the concept of CO_2 as a resource and its implications for the hard to abate industries' emissions mitigation.

4. Carbon Capture Utilization and Storage

From the previous analyses, CCS resulted to have some limitations, since geological sites are finite and some of them will quickly reach capacity. For this reason, the main focus of this chapter is on how to optimize underground storage by coupling it with CU (Carbon Utilization) in CCUS (schematized in Figure 50, taken from [34]), to avoid the saturation of geological sites, while simultaneously generating revenues.

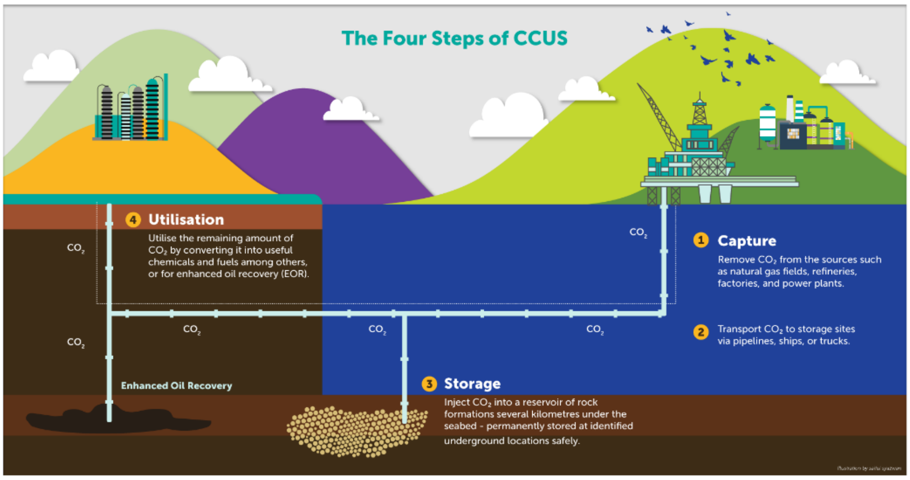


Figure 50: Scheme of CCUS steps, taken from [34]

In fact, there are several markets and applications in which CO_2 can be resold, enabling to convert it from being a liability for the climate system and the industries to being an asset for both emitters and users. In this context, firms and industries are incentivized to develop CCUS systems to obtain both environmental and economic benefits from these additional practices and/or by reselling their CO_2. In general, adding CCU to CCS systems leads to many benefits like the enrichment of the portfolio through the production of value-added products, the circularity of recovering products instead of wasting them, the possibility to exploit CCS even in regions with low storage capacity, and the possibility of covering (partially or completely) the costs of implementing CCS systems in a firm. CO_2 can be “stored” for varying amounts of time through CCU, as long as the obtained product remains in use. In fact, these products must assure long times before the CO_2 is re-released by combustion or degradation. Uses of CO_2 include the production of chemicals (urea, refrigerants, inert agents for food packaging, carbonates, etc..). In Figure 51, taken from [35], is reported a scheme of CCUS’s possibilities, that are now going to be analyzed in details.

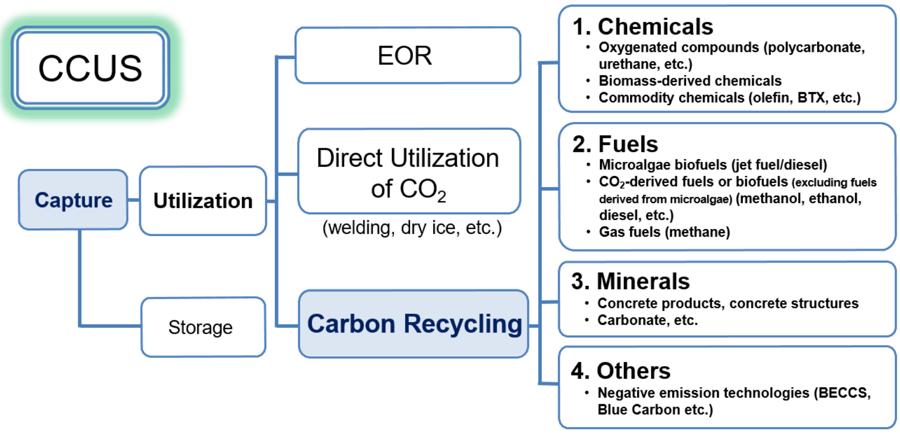


Figure 51: CCUS scheme, taken from [35]

4.1 Applications

Carbon Utilization includes different types of technologies that aim at converting the captured CO_2 into valuable products and materials (building materials, chemicals, and fuels). The 2021 research "A review of carbon capture and utilisation as a CO2 abatement opportunity within the EWF nexus" by Ikhlas Ghiat and Tareq Al-Ansari [36] recognizes five main categories of CO_2 applications: chemical conversion, mineral carbonation, enhanced oil recovery, biological conversion and direct utilization, which are reported in Figure 52, taken from the stated study [36].

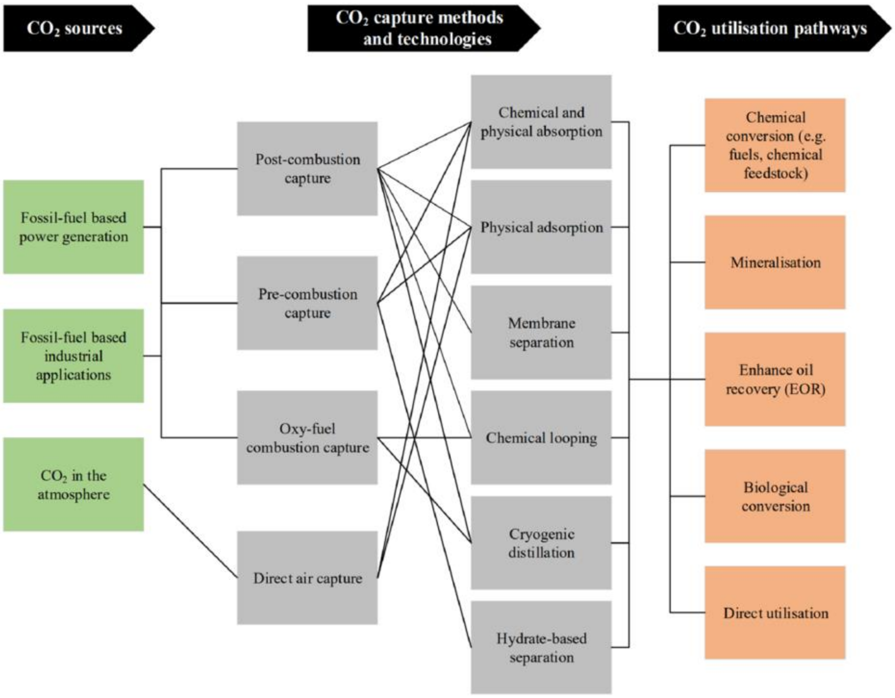


Figure 52: CCUS utilization pathways, taken from [36]

4.1.1 Conversion to chemicals and fuels

This category includes the production of several chemicals (examples are salicylic and formic acid, urea, organic and cyclic carbonates, polycarbonates and fine chemicals) starting from the captured CO_2. Between the cited ones, urea is considered as the one with the largest market size as agricultural fertilizer and other applications. Moreover, CO_2 can be used as a source of carbon for the production of synthetic fuels such as methane, methanol, and syngas, in processes of hydrogenation to other compounds, which are schematized in Figure 53, taken from [37].

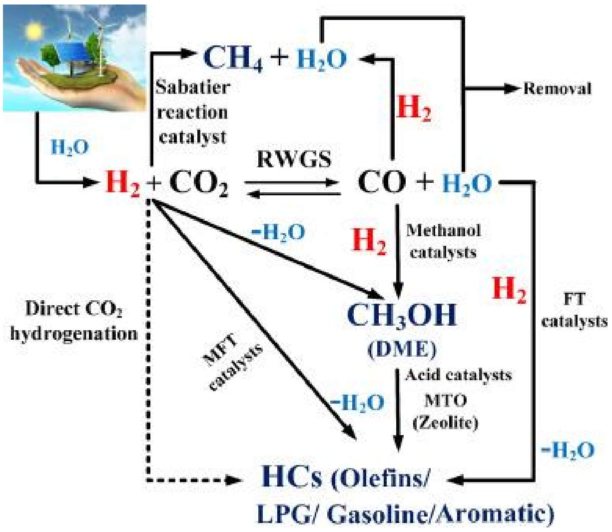


Figure 53: Hydrogenation processes of CO_2, taken from [37]

The first step of these processes consists in the capture of CO_2 from industrial emissions (hard-to-abate sectors) and cleaning it from impurities and water. There are then different possible paths, for example through a conversion called Reverse Water Gas Shift (RWGS), CO_2 can be converted to CO, and then the obtained carbon monoxide can go through other processes to obtain synthetic fuels, like paraffins, olefins, gasoline, methanol or methane. Otherwise there is also the possibility to directly convert CO_2 to these compounds.

These reactions include:

1. Sabatier reaction to obtain methane: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_20$;
2. Fischer-Tropsch Synthesis (FTS) to hydrogenate CO to liquid hydrocarbons HC (which are the basis for synthetic fuels): $(2n+1)H_2 + nCO \rightarrow C_nH_{(2n+2)} + nH_2O$;
3. Modified FTS to directly hydrogenate CO_2 to liquid fuels through the use of Fe-catalysts, that exhibit both RWGS and FTS activities;

4. Methanol Synthesis, composed of three reactions: CO_2 hydrogenation to methanol ($CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$), RWGS reaction and CO hydrogenation to methanol ($CO + 2H_2 \rightarrow CH_3OH$);
5. Methanol-to-Gasoline (MTG) to convert methanol to hydrocarbons that can be used as gasoline or blend stock;
6. Methanol-to-Olefins (MTO) to convert methanol to light olefins that can be used to produce polymers or liquid hydrocarbons (or they can be further converted to gasoline through oligomerization);
7. Modified MTG to directly hydrogenate CO_2 to HC using a bifunctional catalytic bed;
8. Modified MTO to directly convert CO_2 into light olefins.

Also the production of fuels from biomass falls in this category, in fact through photosynthesis, water and CO_2 can be converted into energetic organic compounds (e.g. starch), that can then be converted into industrial fuels like methane, methanol, hydrogen or biodiesel.

These operations give an important value to the stored CO_2, as the obtained products can be then distributed and used as a fuel resource instead of fossil ones, resulting suitable for a wide range of applications, from transportation to heating and electricity generation. In fact, as already stated, these generated liquid hydrocarbons can be further refined and processed to produce a variety of synthetic fuels, including Synthetic Natural Gas, Synthetic Diesel or Jet Fuel, Methanol, Dimethyl Ether (DME). Example of applications are: the Synthetic Natural Gas can be used for heating, electricity generation and transportation, Synthetic Diesel or Jet Fuel are suitable for use in existing internal combustion engines and aviation, Methanol is a liquid petrochemical that can serve as a fuel in transportation or as a feedstock/solvent for other chemicals, and DME is another fuel and chemical product.

This utilization pathway of CO_2 guarantees several improvements, like the abatement of CO_2 emissions from the industrial and the power sectors and the additional sustainable production of fuels and chemicals, obtained starting from wasteful CO_2 emitted from different industrial sources, reducing the use of fossil fuels.

4.1.2 Mineral carbonation

Mineral carbonation is another possible CO_2 utilization pathway that consists of fixing CO_2 as insoluble carbonates, through a reaction of mineralization between captured carbon dioxide (high concentration) and metal oxide bearing materials, like natural minerals, solid wastes or wastewaters containing metal ions. A schematic of this technique is reported in Figure 54, taken from [21].

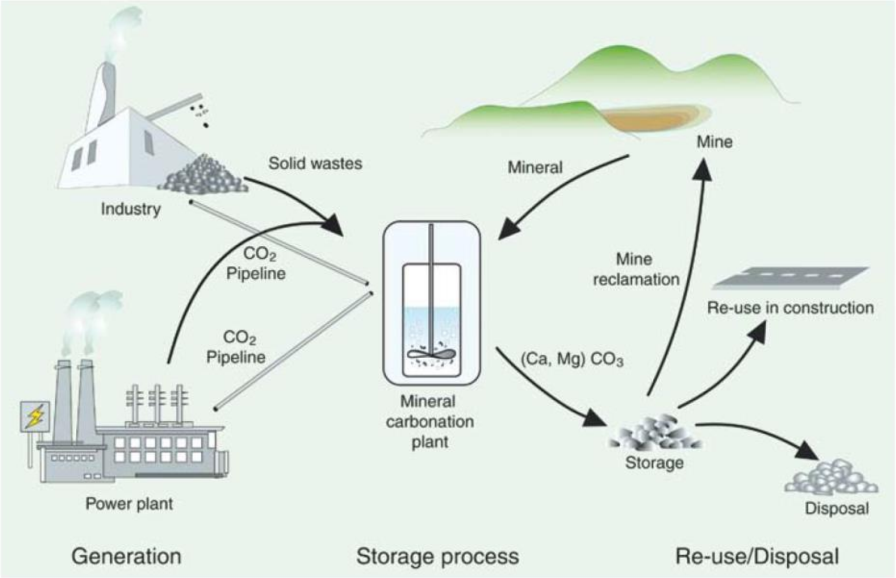


Figure 54: Scheme of mineral carbonation, taken from [21]

The chemical process of carbonation naturally occurs in silicate weathering due to reaction of metal oxides with atmospheric CO_2, following the reaction reported below:

$MO + CO_2 \rightarrow MCO_3$ + heat

MO stands for Metal Oxides (M is a divalent metal, e.g. magnesium, iron or calcium). At ambient temperature and low partial pressure of atmospheric CO_2, this reaction occurs spontaneously, yet at geological time scales, therefore it is fundamental to find options to speed it and utilize the heat of reaction. Mineral carbonation results of interest due to the abundance of metal oxide bearing materials and the long permeance times of CO_2 in a stable solid form.

Value-added products that can be obtained are calcium carbonate ($CaCO_3$, used in both in the pharmaceutical and the construction sectors), magnesite ($MgCO_3$, used for refractory bricks, flooring, fireproofing, cosmetics, etc..), hydrotalcite (used as a catalyst).

4.1.3 Enhanced oil and coal-bed methane recovery

Two other CO_2 utilization pathways are represented by Enhanced Oil Recovery (EOR) and Coal-Bed Methane Recovery (ECBM), in which production of previously unrecoverable volumes of oil or gas from depleted fields is obtained through the injection of CO_2 in the supercritical form (it easily mixes with oil, reducing its viscosity to better displace it and facilitate the production). This process leads to an increase in the production yield, that ranges from 30% to 60% (instead of 20%-40% of the conventional method). A schematic of this technique is shown in Figure 55, taken from [38].

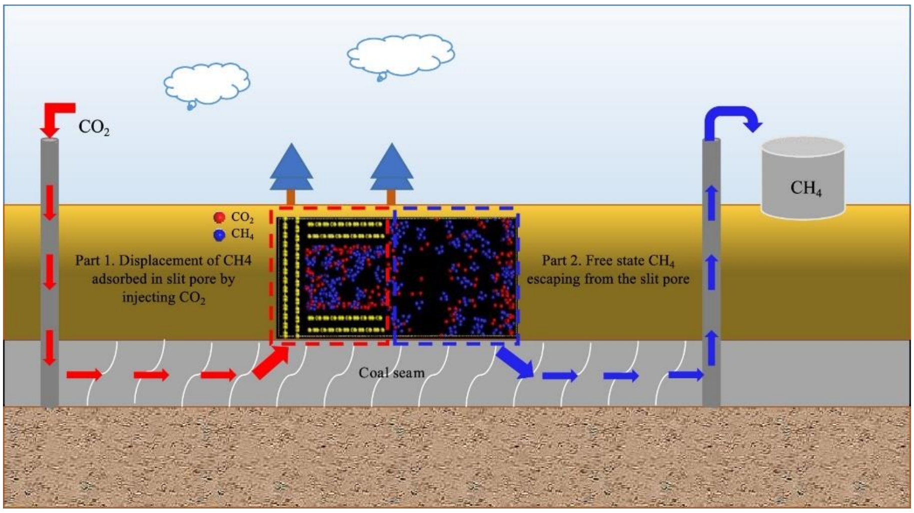


Figure 55: ECBM technique's schematic, taken from [38]

ECBM is currently not practiced due to economical unfeasibility, on the other hand EOR has been performed for now over 40 years in the oil industry. EOR nowadays represents the largest opportunity for CO_2 utilization and brings with it the concept of carbon negative oil, since, with proper applications the net emissions of CO_2 of the whole process of oil can reach neutral, or even negative levels. This application allows to increases oil production and also to obtain secure storage of CO_2 in depleted oil and gas reservoirs, that have already been studied, modelled and equipped.

4.1.4 Biological conversion

Biological conversion of CO_2 is another utilization pathway that consists in the use of microorganisms that use CO_2 as carbon source for the production of bioproducts (e.g. biofuels and bioplastics). This technique is referred to as Biological Carbon Capture and Utilization (BCCU), and a schematic of it is reported in Figure 56, taken from [39].

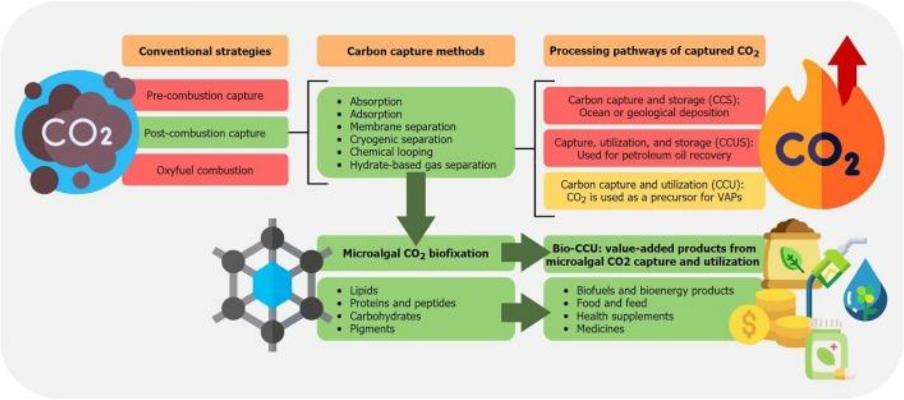


Figure 56: BCCU technique's scheme, taken from [39]

CO_2 is absorbed and fixed through photosynthesis by algae and/or other terrestrial crops, that convert it into organic carbon. Microalgae present many peculiar features that make them an optimal option for BCCU, for example they have a fast growth rate in presence of high concentrations of CO_2, that leads to increasing fixation capacity (way higher than terrestrial crops), and they can also be converted into a biodegradable and carbon neutral biofuel.

In the context of BCCU, also other processes are of interest, for example photosynthetic cyanobacteria are important for the production of bioethanol, since they are able to use the captured CO_2 to produce organic matter. Moreover, it is useful also to mention the utilization of CO_2 to grow bacteria for the production of microbial proteins (MPs), which are usually used as animal feed and are considered important alternatives to animal- and plant- based proteins. The strong opportunity given by this technique, in addition to the benefits provided in general by CCUS practices, is the reduction in land use and water consumption usually dedicated to the cultivations. The general scheme of this practice is reported in Figure 57, taken from [40].

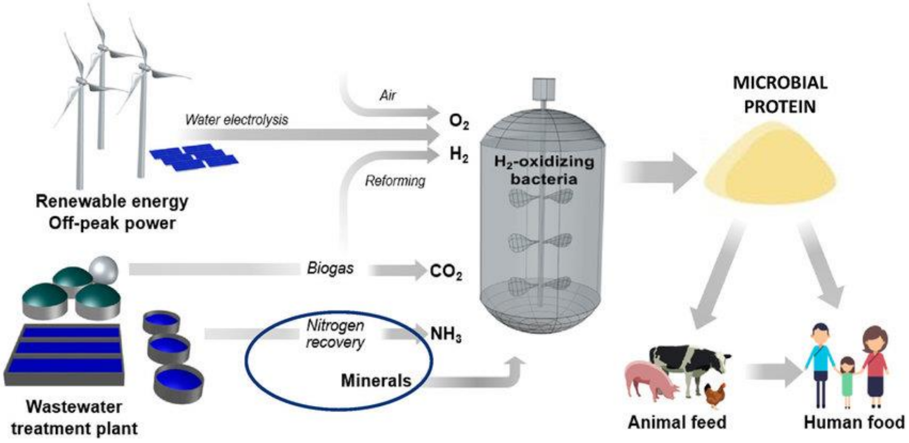


Figure 57: General scheme of Microbial Proteins production, taken from [40]

Lastly, another BCCU option is the commercial practice of CO_2 enrichment in agricultural greenhouses, used to increase the crop's productivity. In fact, high concentrations of CO_2 can enhance the growth of plants and their yields. In this way the captured CO_2 from industrial sources can reduce the request for fossil fuels in this area.

4.1.5 Direct utilization

The last CO_2 utilization pathway is direct utilization. This include many different options that are practiced in several chemical and industrial sectors, like heating and cooling (CO_2 as a refrigerant), food and beverage (CO_2 is used for carbonation of beverages and also for preservation of foods) and other ones. Examples of products are succinic (used in the food industry, in the cleaning sector and in the pharmaceutical industry) and refrigerants. This pathway can help to decrease the deployment of resources (e.g. water and energy) in these sectors.

4.1.6 Carbon based materials

Another utilization pathway of interest for CO_2 that was not previously listed, since it also includes some of the previously mentioned ones, is through carbon-based materials, like carbon nanotubes and graphene, that have several applications in electronics, materials science, and also in construction as reinforcement materials. Moreover, carbon-based materials can be used as energy sources to replace fossil fuels and for environmental remediation. These materials have optimal properties, like the generation of clean energy by the reduction reaction of oxygen, the degradation of organic pollutants and the photocatalytic generation of H_2. In Figure 58, taken from [41], are reported examples of these materials, obtained from solid carbon.

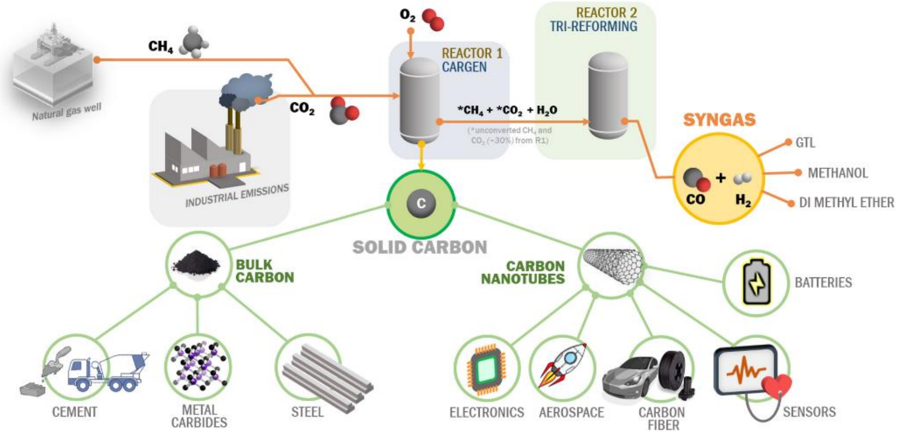


Figure 58: Examples of carbon based materials, taken from [41]

4.2 Existing projects

The IEA 2023 “CCUS projects database” [42] [43] tracks the state of CCUS projects worldwide that have been commissioned since the 1970s up to February 2023, with an announced capacity higher than 100000 t/year. In the dataset, projects are categorized basing on whether they perform capture, full chain, transport, storage, or CCU, and it also specifies the sector of the point source and fate of CO_2. For the aims of this report, some examples of full chain (comprehending both CCS and CU) and CCU projects in some of the countries and areas that resulted to be the most promising for innovation of CCUS (OECD) and also in some that resulted as the most impacting (e.g. China) will be reported, to highlight that this technology is already viable for the hard to abate industries.

4.2.1 ANRAV CCUS

The first one is the currently under construction project named ANRAV-CCUS, in the Devnye cement plant of Heidelberg Materials in Bulgaria. This system is expected to start operating in 2028 and aims to be the first CCUS system in Eastern Europe. It will capture CO_2 emissions from the cement facilities with a hybrid and staged oxyfuel/amine system, with the aim of maximizing the amount of CO_2 that is sequestered from the cement kiln (maximum purity level) while also minimizing the energy utilization and technical risks. The captured CO_2 will then be transported, through an onshore and offshore system of pipelines, to the Galata depleted gas field in the Black Sea, with a capacity of around 0.8 Mt CO_2 equivalent per year [43] [44]. This system already in the first ten years of operation, will lead to avoid 95% of GHG emissions that would have occurred without it (7.8 Mt CO_2 equivalent over the first ten years). The project obtained an EU grant of 190 million euro and also receives private investments. It represents a pilot project for an economically viable way to decarbonize the cement industry in Eastern Europe.

4.2.2 CalCapture CCS + Elk Hills power plant

Another example is the CalCapture CCS + Elk Hills power plant (CA) project by Next Carbon Solutions and California Resources Corporation to decarbonize the CRC’s Elk Hills Power Plant (power and heat sector) through a post combustion capture system, from which the captured CO_2 will be transported and utilized for storage in oil producing reservoirs (EOR). The main objective is to meet California’s energy requirements while reducing the carbon intensity of the plant (expected to capture up to 95% of CO_2 emissions at the Elk Hills Power Plant). This project has the potential to produce the first homegrown net zero barrel made in California, with a capacity of 28 million metric tons of CO_2 over its project life [44], representing a scalable carbon solution for achieving California's energy targets.

4.2.3 Sinopec Shengli Power Plant CCS

Another interesting project is the one in China aimed at decarbonizing the Shengli Power Plant in Dongying, through post-combustion capture system and then utilize the CO_2 for EOR in the Shengli oil fields, to increase recovery by 10%-15% [45]. The system should capture around 110 tons per day of CO_2 (or 3,500 tons per year). At the storage site, located at 80 km of distance, an injection of 1.0 Mt CO_2/yr is expected, with a total expected storage capacity of 21-30 Mt CO_2 [46]. This project, together with another one previously launched by Sinopec (Qilu Petrochemical-Shengli Oilfield CCUS Project), results of paramount importance to demonstrate the feasibility of CCUS in China’s EOR sector to reduce carbon emissions. Sinopec’s projects are examples of the great significance of developing large-scale CCUS systems. They result also of great importance to build a system of “carbon circulation” for China, as this country resulted to be the highest CO_2 emitters, and mitigating projects are now necessary to reach the peak of emissions and later carbon neutrality.

4.2.4 Santos Port Botany, New South Wales (CCU)

An interesting CCU project is the one of the Australian-based manufacturer and supplier of plastics, Qenos, in collaboration with Santos, based on exploiting blue hydrogen as a clean energy source to replace part of the ethane utilized at Qeno’s Port Botany facility in Sydney and reduce its emissions. The goal is to supply up to 2 PJ/yr of blue hydrogen [47]. This project is of particular interest due to the possibility of using plastic waste as a feedstock, which could represent a mitigation pathway for manufacturers.

4.2.5 Steelanol CCU

In Belgium, the iron and steel company ArcelorMittal and LanzaTech Global Inc. is developing an innovative commercial-scale CCU facility (Steelanol) in Ghent, aimed at capturing CO_2 from steelmaking flue gases and biologically convert it into advanced ethanol. The obtained ethanol can then be further utilized to produce several products (e.g. sustainable transport fuels, packaging materials, apparel, and cosmetic fragrances), allowing to make significant steps towards decarbonizing the chemical sector. The facility has a production capacity of 80 million liters of advanced ethanol per year (almost half of the total request in Belgium) and is expected to reduce Ghent plant's emissions by 125000 ton/yr [48]. It is a valid example of the opportunity offered by using CCU to capture emissions and make everyday products at industrial scales.

4.2.6 Avedøre and Asnæs Power Station (Ørsted)

The Danish 'Ørsted Kalundborg Hub' project consists in a system allowing to capture and store around 430000 tons of biogenic CO_2 per year by 2026 [49]. Ørsted's carbon capture system will be applied to two combined heat and power plants, that both work on sustainable straw and wood chips: the wood chip-fired Asnæs Power Station in Kalundborg in western Zealand and the Avedøre Power Station's straw-fired boiler in the Greater Copenhagen area. The captured CO_2 will be shipped to the Northern Lights storage reservoir in the North Sea. The project will use an infrastructure that will function as a system for capture and shipment of its biogenic emissions, and it will also allow the shipping of emissions from other producers. Moreover, it has also been established, through a collaboration between Ørsted, Aker Carbon Capture, and Microsoft, to develop a commercial system to combine carbon capture with clean energy production through biomass-fired CHP plants, exploiting the heat surplus produced by the capture system. Combining the capture process at Avedøre Power Station's straw-fired boiler and the one at Asnæs Power Station, the total surplus of heat should reach around 85 MW (respectively 35 MW and 50 MW), allowing to satisfy the annual district heating demand of around 11k – 20k households in Denmark. This project is a significant example of the commercial value of CCUS activities, and it demonstrates how this solution can develop and mature through policy making and promotion, allowing it to operate on market terms.

Conclusions

This thesis has been developed with the aim of analyzing Carbon Capture and Storage and its potential as a mitigation strategy for current and future CO_2 emissions in the hard-to-abate sectors, in order to comply with the net-zero emissions targets for 2030 and 2050. From the reported evaluations it results that CCS is a significant opportunity in this context, and further deployment of capture, transport and storage systems actually represents a significant and valuable option to abate industrial emissions, especially if coupled with utilization processes.

In the first chapter, CO_2 emissions have been analyzed both in the form of historical data and future projections in different SSP scenarios. From this analysis, future amounts of emitted CO_2 from the hard to abate sectors have been evaluated, also providing a subdivision of the world in five macro regions, composed of different countries with similar emissions trends and behaviors: ASIA, LAM, MAF, OECD and REF. The region with the highest emissions resulted to be Asia, with China and India driving most of its impact. Moreover, OECD countries as well resulted to have a significant impact on emissions that is also expected to rise. In this region, the United States of America resulted as the most impacting country. For this reason, Asia and the OECD regions resulted as the ones to which it is necessary to dedicate particular efforts in mitigation, also due to technological advance present in all OECD countries.

Consequently, after an overview of the CCS technology, the second chapter reports a critical analysis of the literature and databases regarding the volumetric capacity available for underground storage of CO_2. In this context, it is important to note that significant efforts are required to increase the amount of available, complete and comparable studies and databases on the topic. After a deep research, the chosen source has been the MIT report “Developing a Consistent Database for Regional Geologic CO_2 Storage Capacity Worldwide”. This study represents a first step towards creating a consistent database of underground global and local storage capacities; however, it still does not provide a complete dataset, comprehensive of value for all the different nations evaluated under the same hypothesis and with the same methodology, since it mainly provides values for regions, macro regions and countries of interest. Therefore, also the definition of a rigorous and internationally recognized methodology for local evaluations would result in consistent and comparable values, since nowadays all the local estimates are usually based on different assumptions and follow slightly different methodologies. A database of this type would result to be very useful for decision making in the different nations, and also to compare values between neighboring countries without the need of performing each time a new analysis.

In the third chapter, after comparing the emissions data with the storage capacity ones, it was possible to state that, in terms of volumes CCS represents a palpable option for the mitigation of hard-to-abate emissions to reach the goals of the 2030 and 2050 Net Zero Targets. In addition, also a feasibility analysis of this technology has been undertaken, which lead to the conclusion that CCS systems are currently a cost-effective option for emissions' abatement in the hard to abate sector. However it also resulted that, for other industrial sectors this option still results too expensive and complex, and the deployment of other options (like renewable energy sources) is suggested. Being the hard to abate sectors the ones of interest in this study, these findings still resulted positively. However the evaluation of options to reduce costs and complexity of CCS to allow a larger deployment would be beneficial for the research and the investments that are dedicated to this technology. The main finding of this chapter is that, even if storage capacity results to be enough for reaching the Net Zero Targets, in some cases the available volumes are not even enough to cover the amount of CO_2 emissions that are expected until the end of this century. In this context, only deploying CCS systems would imply to be postponing the problem related to industrial emissions, and even if CO_2 concentration in the atmosphere would initially decrease, it would eventually start rising again, once the storage sites reach capacity. For this reason, it is necessary to simultaneously focus on finding innovative solutions and techniques to abate emissions also in the hard to abate sectors.

One possible solution, that is analyzed in the last chapter, is to develop Carbon Capture, Utilization and Storage (CCUS) or Carbon Capture and Utilization (CCU) systems, as a way to not only capture CO_2, but also to give it economic value and allow to re-use it, instead of just storing it. In this way, this systems allow to make a profit from capture, that as previously stated, results in many cases to be too expensive. Some examples of CCUS and CCU system have been reported to highlight the viability of these processes. From the last chapter, it is in fact possible to deduce that by considering CO_2 as a resource and exploiting all the possible pathways of utilization, it is possible to mitigate CO_2 emissions and also create economic advantages for the CCS's systems, developing a comprehensive, circular carbon economy. This synergy allows to reduce emissions, alleviate the burden on storage sites, and stimulate economic growth. In essence, the revenue-generating aspect of CU ensures that CCS projects are not only environmentally responsible but also financially sustainable, fostering a holistic approach to climate mitigation.

The main limits in this research are posed by the lack of detailed and comparable data on local underground storage capacities and, as previously stated, further investigation on the topic is required. It is also important to state that, to be as cautionary as possible, only the lower values of storage capacities have been used (globally 8000 Gt instead of the 55000 Gt of the upper bound), implying that much more volume may be available, making CCS even more useful and interesting. In fact, if way higher volumes were actually to be available, the stated necessity for deployment of CCS in combination with CU would be weaker, especially in this current century. Lastly, more investigation on the actual numerical revenues that CCU can offer are required. In fact, in many of the reported examples, the investments were almost always stated in the presentations, and sometimes also the unit value of the obtainable final product. However, to make this options more intriguing and valuable, it would be useful to enrich these reports with costs analysis, comprehensive of values of payback time of CCU and CCUS technologies.

In conclusion, the outcomes of this thesis emphasize the promising potential of carbon capture and storage (CCS) as a viable mitigation strategy for hard-to-abate systems. When synergistically combined with carbon capture and utilization (CCU) technologies, these approaches offer a multifaceted solution to address the complex challenge of reducing carbon emissions in these industries, while also creating opportunities for turning captured carbon into valuable products. This not only mitigates emissions but also provides economic incentives. Moreover, the research has recognized the importance of ongoing technological advancements, research, innovation and investments in CCS and CCU to make them increasingly cost-effective and viable for widespread adoption. In this context, also effective policy and regulatory frameworks, obtained from the collaboration between governments and industry stakeholders, play a fundamental role in the successful deployment of CCS and CCU. In fact, the success of this approach is contingent on comprehensive support from governments, industries, and the scientific community. The implications of CCS and CCU extend beyond individual nations, and their successful deployment can contribute significantly to global efforts to combat climate change and decarbonize various challenging sectors.

This thesis, by shedding light on the promise of CCS and CCU within hard-to-abate sectors, contributes to the ongoing discourse and action needed to address one of the most pressing challenges of our time: mitigating climate change and ensuring a cleaner, more sustainable world for future generations.

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