

CARBON CAPTURE STORAGE TECHNOLOGIES: REALITIES, BOUNDARIES AND PERSPECTIVES

Isachi Silvia Elena

Scientific Researcher, Centre of Financial and Monetary Research “Victor Slăvescu”

Abstract: Carbon capture and storage (CCS) technologies are a key technological solution in the global effort to reduce greenhouse gas emissions. These technologies are particularly important in hard-to-decarbonize industries, where alternative options are limited. However, CCS implementation still faces technical, economic and regulatory hurdles. Key challenges include high costs, low energy efficiency of processes, lack of infrastructure for carbon transport and storage, and regulatory uncertainties. Low public acceptance and concerns about the safety of long-term geological storage also contribute to the slow pace of large-scale adoption. This paper provides an analysis of the current state of CCS technologies, identifying the main limitations and highlighting development prospects. We will therefore examine the research directions and policies needed to support sustainable implementation, in line with international climate goals.

Keywords: carbon dioxide capture, geological storage, industrial decarbonization, climate policy technological challenges.

Introduction

Climate change is one of the most complex issues facing humanity, with significant implications for ecosystems, economies and societies around the world. Greenhouse gas emissions, especially carbon dioxide (CO₂), mainly generated by human activities, contribute significantly to global warming. Limiting the increase in the global average temperature to below 2°C, with the ambition not to exceed 1.5°C, has become a priority objective at international level, enshrined in the Paris Agreement. In this context, the energy transition involves not only expanding the use of renewable sources and improving energy efficiency, but also developing advanced technological solutions, such as carbon capture and storage (CCS), which play an important role in reducing emissions from high-impact industrial sectors.

CCS is a set of technologies that facilitate the capture of carbon dioxide (CO₂) emitted from industrial processes or fossil fuel-fired power plants. This CO₂ is then transported and stored safely in deep geological formations to prevent its release into the atmosphere. Many experts consider this solution essential for achieving climate neutrality, especially in sectors where electrification or other low-emission technologies are difficult to implement. CCS is also included in the mitigation scenarios developed by the Intergovernmental Panel on Climate Change (IPCC), which warns that without its use, the costs of the energy transition could increase significantly.

At European level, carbon capture and storage (CCS) is considered a transitional technology, capable of allowing the continued use of certain fossil energy sources in a way that is consistent with decarbonisation objectives. It is one of the few technological solutions available to reduce residual emissions from industrial processes, such as cement, steel or fertiliser production, where alternatives are still underdeveloped. However, the large-scale implementation of CCS has been slow so far, and the number of commercial projects is relatively small compared to the estimated needs. The delays are due to several challenges, including technological difficulties in efficiently capturing CO₂, the absence of dedicated transport infrastructure, legislative

uncertainties related to long-term responsibility for storage and, last but not least, a low level of public acceptance. These difficulties cause hesitation among investors and public authorities, thus influencing the pace of development of the technologies.

The aim of this paper is to analyze the current state of carbon capture and storage (CCS) technologies, to identify the main obstacles limiting their adoption, and to highlight the research, innovation and policy perspectives needed for their effective integration into decarbonization strategies. The study is based on a literature review and adopts a multidimensional approach, considering both technical and economic aspects, as well as legislative and social ones.

Theoretical and technological foundations of carbon capture and storage (CCS)

Carbon capture and storage (CCS) technologies consist of a series of processes designed to prevent the release of CO₂ into the atmosphere. They involve capturing carbon dioxide at source, transporting it to a suitable location and injecting it into safe geological formations for long-term storage. The CCS process generally involves three main steps: capture, transport and storage.

- a) CO₂ capture is the first essential step in the CCS technological chain and is achieved by separating carbon dioxide from flue gases or concentrated industrial streams. There are three main capture methods:
 - Post-combustion capture: This method is applied after the combustion of fuels and involves separating carbon dioxide (CO₂) from exhaust gases, which contain relatively low concentrations of CO₂ (approximately 10–15%). It is compatible with existing energy infrastructure and typically uses chemical solvents, such as amines, to absorb CO₂.
 - Pre-combustion capture: This technique involves converting fossil fuels into synthesis gas (syngas), followed by separating the CO₂ before combustion. Although this process is more energy efficient, it requires significant plant modifications.
 - Oxy-combustion: This method involves burning fuels in an environment of pure oxygen, instead of air, resulting in a flue gas composed mainly of CO₂ and water vapor. This simplifies the process of carbon dioxide capture.

Each method of emission capture has both advantages and limitations, depending on the type of emission source, the efficiency of the process and the associated costs. Recent research focuses on improving absorption materials, reducing energy consumption in the capture process and developing more efficient separation methods. In order to assess the impact of various industrial sources on global carbon dioxide emissions, a quantitative analysis of them is crucial.

Table 1 provides an overview of the main emitting sectors, presenting estimates of annual global CO₂ emissions, expressed in gigatonnes. This distribution facilitates the identification of priority sectors for the implementation of carbon capture and storage (CCS) technologies, depending on their effect on the climate balance. The information presented, based on currently available estimates, is essential for developing decarbonization strategies and for outlining directions in energy and industrial policies.

Table 1: Comparison of the main CO₂ capture methods

Capture method	Applicable stage	Purity of CO ₂ obtained (%)	Energy efficiency	Estimated cost (\$/tonne CO ₂ captured)	Estimated cost (\$/tonne CO ₂ captured)
Post-combustion	After burning	85–95	Low	40–80	High (TRL* 8–9)
Pre-combustion	Before burning	95–99	Average	30–60	Medium (TRL 6–8)
Oxi-combustion	During combustion	90–95	low – average	50–90	Medium (TRL 6–7)

*TRL = Technology Readiness Level (technological maturity level, 1–9)

Source: author data processing after the IPCC report (2005) and Bui, Adjiman, Bardow, Anthony, Boston, Brown, Mac Dowell, (2018).

Table 1 summarizes the main characteristics of the three CO₂ capture methods, highlighting the differences in efficiency, purity of the captured gas and associated costs. Post-combustion capture, although less efficient, is the most technologically developed and most frequently used in commercial applications. On the other hand, pre-combustion capture offers higher purity and better yield, but involves additional costs for adapting the facilities. Oxycombustion, although promising, is still in the testing stage.

- b) *CO₂ transport* - after capture, carbon dioxide is compressed to a supercritical state and transported, usually through pressure pipelines to storage sites. Pipeline transport is the most developed and used technology in the gas industry. In certain situations, transport can also be carried out using road or naval tankers, especially when the volume is small or the distances are long. The safety and integrity of the transport system are essential and are regulated by strict rules aimed at monitoring pressure, preventing leaks and maintaining optimal operating conditions.
- c) *Geological storage of CO₂* - the last stage of the carbon capture and storage (CCS) process involves injecting carbon dioxide (CO₂) into deep geological formations, where it can be safely stored for the long term. The most common types of storage sites include:
 - depleted hydrocarbon reservoirs: former oil or natural gas fields that have already demonstrated the ability to retain fluids under pressure.
 - deep saline aquifers: porous formations filled with salt water, which offer a large volume of storage and are geologically abundant.
 - unminable coal seams: which can retain CO₂ by adsorption, although this option is less technologically developed.

In general, CCS technologies are at a variable stage of technical maturity, with limited commercial applications and considerable costs. However, recent advances in research and development suggest significant potential for process optimization, especially through integration with other emerging technologies, such as Direct Air Capture (DAC) or low-emission hydrogen production.

The adoption of carbon capture and storage (CCS) technologies on an industrial scale depends largely on their technological maturity and economic feasibility in various sectors.

Table 2 provides a summary of the main CO₂ capture technologies, highlighting their stage of development (assessed by the Technology Readiness Level – TRL), their areas of applicability and relevant operational characteristics. This classification facilitates understanding the

differences between existing technologies and their potential for implementation in different industrial contexts. It also serves as a starting point for analyzing technological barriers and for guiding future R&D investments.

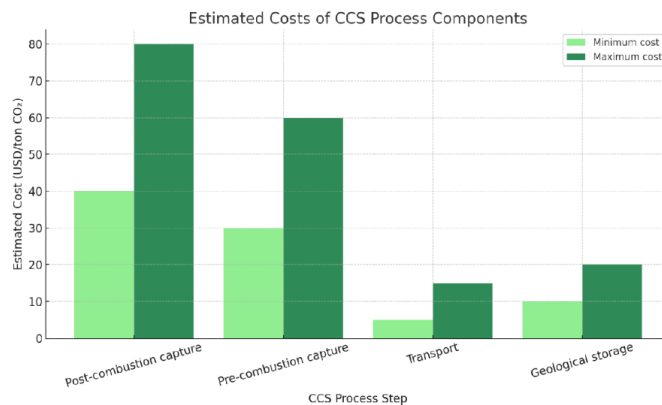
Table 2: Types of CO₂ geological storage sites

Storage type	Typical depth (m)	Estimated storage capacity (Gt CO ₂)	Usage examples	Advantages	Limitation
Hydrocarbon reservoirs	800–3000	900–1200	Norvegia (Sleipner)	Existing infrastructure	Limited volume in some regions
Deep saline aquifers	>1000	1000–10.000	Canada, SUA	Wide availability	Requires detailed characterization
Unexploitable coal seams	300–1500	3–200	Australia	Possibility of methane recovery	High risk of CO ₂ migration

Source: author data processing according to the IPCC (2005), IEA (2019) and CSLF (2017) reports.

Table 2 provides a comparison of the main types of geological formations used for CO₂ storage. Deep saline aquifers have the largest storage capacity globally, but require detailed geological characterization and post-injection monitoring. Hydrocarbon reservoirs are preferred due to their existing infrastructure and in-depth geological knowledge. Coal beds can facilitate methane storage and recovery, but pose greater risks in terms of stability.

To highlight the economic differences between industrial sectors in the application of CCS technologies, **Figure 1** illustrates the estimated cost ranges for capturing one tonne of CO₂ in key industries. The values presented include both minimum and maximum costs, highlighting the variability of the data depending on factors such as the technology used, gas flow characteristics and operating conditions specific to each sector. This graphic representation provides a comparative perspective on costs, constituting an essential tool for prioritizing investments and identifying the most cost-effective areas for CCS deployment.



Graficul 1: Costurile estimative ale proceselor CCS (USD/tonă CO₂)

Source: author data processing after Rubin, Davison, Herzog (2015) and the Global CCS Institute (2023) and IEAGHG (2020) reports.

Capture is the most expensive step, with significant variations depending on the technology used and the source of emissions. Transport and storage costs are lower, but can become significant in the absence of a well-developed regional infrastructure. Current estimates indicate a total cost of between 60 and 115 USD per ton of CO₂, which poses challenges in terms of the economic competitiveness of these solutions in the absence of financial support mechanisms.

Analysis of economic and energy factors in the implementation of CCS technologies.

- a) *Direct and indirect costs of implementation.* The implementation of carbon capture and storage (CCS) technologies involves a complex cost structure, which differs depending on the industrial sector, the technology used and the geographical location.

In general, the costs are divided into three main categories:

- CO₂ capture – represents the most expensive stage, constituting up to 70% of the total cost of the CCS chain. These costs include the initial investment in facilities, maintenance and the energy required for gas separation.
- CO₂ transport – involves the construction of pipelines or the use of other methods, such as tanker or ship transport. Costs vary depending on the distance traveled and the volume transported.
- Geological storage – includes drilling, geological characterization, injection and long-term monitoring. The costs are lower compared to those for capture, but come with technical risks and strict regulations.

In addition to direct costs, it is important to also consider indirect costs, such as those associated with adapting existing installations, energy efficiency losses, and possible penalties or incentives provided by public policies.

- b) *Impact on energy efficiency of industrial facilities.* A significant challenge in implementing carbon capture and storage (CCS) technologies is the reduction in energy efficiency of power plants and industrial facilities. Depending on the technology used, it is estimated that CO₂ capture can cause:

- a decrease in thermal efficiency by 10–25% for coal-fired power plants;
- an increase in electricity consumption for compression and solvent regeneration units;
- an additional carbon footprint, if the required energy does not come from renewable sources.

Figure 1 highlights that the capture stage is not only the most expensive, but also the most energy - intensive. This situation may make some CCS projects uncompetitive in the absence of appropriate financial support mechanisms or a carbon tax.

- c) *Financing, incentives and support mechanisms.* Due to their high costs, carbon capture and storage (CCS) projects are often difficult to implement without external assistance. Available financing models include:

- government grants and innovation funds, such as those offered by the European Union (e.g. the Innovation Fund);
- compensation mechanisms for reducing emissions, such as carbon credits; - public-private partnerships that share investment risks;
- negative carbon taxes (purchase of carbon credits) for industries struggling to decarbonize.

The existence of effective market instruments and a coherent legislative framework is essential to attract significant investment in CCS infrastructure.

To highlight the significant variations in the costs associated with the implementation of carbon capture and storage (CCS) technologies in different industrial sectors, a comparative analysis is useful. Table 3 presents the estimated average values of CO₂ capture costs, expressed in US dollars per tonne captured, for key high-emission industries. These values are influenced by factors such as: the nature of the gas streams, the technological maturity level (TRL), the energy efficiency of the processes and the adaptability of existing installations. This comparative presentation helps us to identify the sectors where CCS is already economically feasible, as well as those that require additional investment in research and development.

Table 3: Estimated average costs of CCS by industry sector (USD)

Industrial sector	Capture type	Estimated cost (USD/ton CO ₂)	Technology level (TRL)	Relative energy efficiency (%)
Coal Power Generation	Post-combustion	50–90	9 (commercial)	75–85%
Cement	Post-combustion	70–120	7–8 (pilot – demonstration)	65–75%
Steel	Oxy-combustion / pre-combustion	80–150	6–8 (pilot – development)	60–70%
Oil and Gas Refining	Pre-combustion	40–80	8–9	80–90%
Hydrogen from Methane Gas (SMR)	Pre-combustion	30–60	9	85–95%

Source: data processed after Rubin, Davison, Herzog, (2015).

As can be seen, the lowest costs are found in the refining industry and hydrogen production, where CO₂ streams are relatively pure. In contrast, heavy industries such as cement and steel production have higher costs, mainly due to diffuse emissions and complex thermal processes. The Technology Readiness Level (TRL) indicates the maturity of CCS applications in different sectors. Currently, only electricity and hydrogen from methane are fully commercial (TRL 9).

Technological challenges of carbon capture and storage (CCS)

The implementation of carbon capture and storage (CCS) technologies on an industrial scale presents numerous technical challenges, affecting both process efficiency and operating and maintenance costs. Although the fundamental principles of CO₂ capture are well known, the integration of these technologies into complex, often continuously operating, industrial processes involve significant technological hurdles.

CO₂ Capture: Technical Limitations and Integration Constraints. CO₂ capture is the most expensive and at the same time the most challenging step in the entire CCS chain. The concentration of carbon dioxide in the exhaust gas varies considerably depending on the type of emission source, from around 4% in the case of gas-fired power plants to over 20% in cement or hydrogen production processes by steam reforming.

Post-combustion carbon dioxide capture technologies, which use amine solvents such as monoethanolamine (MEA), offer high efficiency. However, they face significant energy consumption for solvent regeneration, which affects the energy performance of the entire plant. Although oxy - combustion is a promising alternative, it requires pure oxygen sources and major modifications to the existing infrastructure. As for pre-combustion, which is more suitable for

gasification processes, it faces scalability limitations in traditional industries such as cement or steel.

CO₂ transport: infrastructure and safety challenges. Transporting captured carbon dioxide requires the development of extensive pipeline networks or the use of road and sea transport. Pipelines are the most efficient option for large volumes, but they present technical challenges, such as corrosion of materials, the need for compression at high pressures, and ensuring safety in the event of leaks. Also, many large industrial sources are located at considerable distances from potential geological storage sites, which generates additional infrastructure costs. Currently, the lack of integrated regional CCS transport networks is a significant obstacle to the expansion of this technology.

Geological storage: uncertainties and technical limitations. Long-term storage of CO₂ in deep geological formations, such as saline aquifers or depleted hydrocarbon reservoirs, requires detailed geological characterization, advanced modeling, and constant monitoring. Key challenges include:

- the tightness of the cap rock;
- the risks of CO₂ migration to other formations;
- the possibility of chemical reactions with host rocks, which can cause geomechanical instability;
- the lack of adequate geological data in many regions.

In addition, continuous monitoring of emissions and subsurface pressure involves the use of advanced sensor systems, expensive geophysical methods, and periodic interventions, all of which contribute to increased operational costs.

Scalability and industrial integration. A significant technological hurdle is the transition of CCS solutions from pilot stages to large-scale commercial installations. Many technologies that have shown success in laboratories or demonstration plants fail to maintain the same efficiency under real industrial conditions. Integrating CCS technologies into existing production processes often requires costly plant adaptations, planned shutdowns and temporary losses of productivity. In addition, the industrial sector is extremely diverse in terms of gas composition, operating temperatures and operating regimes, which complicates the implementation of universal solutions.

In order to better understand the technological barriers encountered in the development and application of carbon dioxide capture (CCS), it is important to make a structured comparison of the main types of technologies used. **Table 4** provides a summary of the technical limitations specific to each method, the degree of technological maturity (assessed by the TRL – Technology Readiness Level) and the industrial sectors in which these technologies are typically implemented. This comparative analysis facilitates the identification of mature technologies, ready for large-scale implementation, as well as those that are in their early stages and require additional research and significant investment in development.

Table 4: Major technical limitations of CCS technologies

CCS technology	Main technological challenges	TRL level	Typical areas of application
Post-combustion (monoethanolamine - MEA)	Energy-intensive regeneration, chemical degradation of solvents	8–9	Energy, cement, refineries
Pre-combustion	Complex infrastructure, limited applicability	7–8	Hydrogen production, chemistry
Oxi-combustion	Requires pure oxygen, significant plant modifications	6–7	Thermal energy, refineries
Solid adsorbents	Variable efficiency, unstable thermal regeneration	5–6	Pilot projects, applied research
Selective membranes	Limited selectivity and flux, sensitivity to impurities	4–5	Light industry, modular capture

Source: data processed after Rubin, Davison, Herzog, (2015), IEAGHG (2020) and Bui, Adjiman, Bardow, Anthony, Boston, Brown, Mac Dowell, (2018).

Post-combustion technologies based on chemical solvents, such as monoethanolamine (MEA), have reached an advanced level of maturity (TRL 8–9) and are already used in commercial plants. However, they require significant energy consumption for solvent regeneration and present corrosion risks. On the other hand, emerging technologies, such as selective membranes or solid adsorbents, are still in experimental stages (TRL 4–6). They show promising results, but face limitations in terms of the volume of CO₂ processed and stability under real industrial conditions. In addition, oxy-combustion technology, although generating a concentrated stream of CO₂, imposes significant infrastructure constraints, requiring pure oxygen supply and considerable modifications to existing plants.

Pre-combustion, used in particular in gas reforming for hydrogen production, faces difficulties in its integration into traditional industries. Thus, the choice of a carbon capture and storage (CCS) technology must be based on the specific characteristics of the targeted industrial process, the availability of infrastructure and the degree of technological maturity, given that there is no universal solution that fits all sectors.

In assessing the performance of carbon dioxide capture technologies, a crucial indicator is the energy penalty associated with the capture process. This is the decrease in the overall energy efficiency of the installation, caused by the additional energy consumption required to operate the CO₂ separation and compression systems. **Figure 2** illustrates a comparison of the average values of the energy penalty, expressed as a percentage, for the main types of capture technologies used in industry.

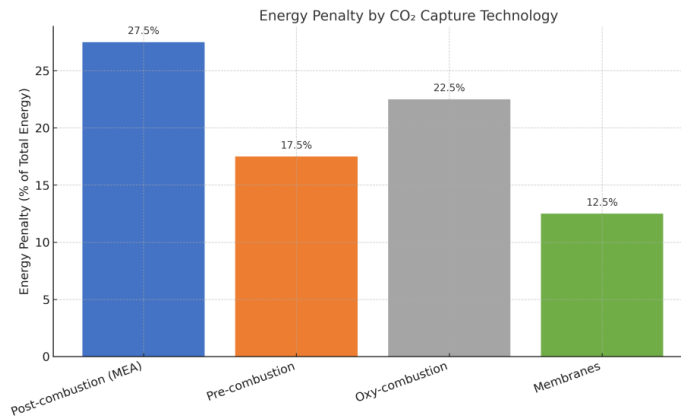


Figure 2: Energy penalty by CO₂ capture technology
 Source: Rubin, E. S., Davison, J. E., & Herzog, H. J. (2015)

Figure 2 illustrates the significant differences in the energy penalty associated with the main carbon dioxide capture technologies. Post-combustion technology, which uses monoethanolamine (MEA), has the highest additional energy consumption, with an average penalty of about 27.5%. This is due to the need to regenerate the chemical solvent used for CO₂ absorption. In contrast, pre-combustion technology, which converts the fuel into a mixture of hydrogen and CO₂ before combustion, has a lower energy penalty of about 17.5%. Oxy-combustion, which involves burning the fuel in a pure oxygen environment to produce CO₂-rich flue gas, generates a penalty of about 22.5%. Emerging membrane-based technologies have the lowest energy penalty of only 12.5%, which gives them promising potential in terms of energy efficiency, although they are still in an early stage of commercial development.

Economic and financial challenges of carbon capture and storage (CCS).

In addition to technological challenges, the large-scale deployment of carbon capture and storage (CCS) technologies is strongly influenced by economic factors. Although CCS is seen as a crucial solution for the decarbonization of hard-to-electrify sectors, the high costs associated with the entire process – from capture to geological storage – constitute one of the most significant obstacles to global adoption.

- *Capital and operating costs.* The initial investments required to deploy carbon capture and storage (CCS) technologies are considerable, varying depending on the type of facility and the industrial sector. Capital costs (CAPEX) include capture infrastructure, transmission pipelines, compressor stations and the development of storage sites. These are complemented by operational costs (OPEX), which cover equipment maintenance, additional energy consumption (energy penalty) and post-injection monitoring costs. A study by the Global CCS Institute (2023) estimates that for a CCS project integrated into a coal-fired power plant, the total cost could exceed \$100/tonne of CO₂ captured and stored, with significant variations depending on region and technology.
- *Lack of stable financing mechanisms.* Without clear carbon pricing policies or a regulatory framework that financially incentivizes emission reductions, most carbon capture and storage (CCS) projects are not economically viable under free market conditions. In addition, uncertainty about long-term government support discourages private investors. For example, mechanisms such as “contracts for difference” or direct subsidies for each

tonne of CO₂ captured, available in some countries (such as the US, Norway and the UK), are absent in many other regions, leading to uneven adoption of CCS technologies globally.

- *Economies of scale and sector-specific costs.* The costs of carbon capture and storage (CCS) vary significantly across industry sectors. Industries that generate concentrated streams of carbon dioxide, such as ammonia or bioethanol production, enjoy lower costs, often below \$40/tonne. In contrast, industries with diffuse emissions, such as cement, face much higher costs, exceeding \$100/tonne. The absence of a functioning global carbon market limits the ability to reduce costs through economies of scale. Without a real demand for carbon capture, such as the use of CO₂ in industrial products or its storage for commercial purposes, CCS remains dependent on public support.
- *Investment risk and capital recovery.* The long payback period of investments in carbon capture and storage (CCS), especially in projects involving transport and geological storage, represents a significant economic obstacle. The recovery of invested capital becomes uncertain in the absence of clear revenue generation mechanisms, either through carbon credits or emission penalty policies. Also, risks related to possible leakage of stored CO₂, strict environmental regulations and post-storage liability can lead to increased insurance premiums and costs for investors.

A comparative analysis of the specific costs for implementing CCS in various industrial sectors provides a clear picture of the economic variability of this technology. The costs per tonne of CO₂ captured and stored are influenced by factors such as the concentration of CO₂ in exhaust gases, the stability of industrial flows, the need for technological adaptations and the distance from a storage site. The **table 5** presents the average cost estimates, highlighting the variation between the minimum and maximum thresholds identified in the literature.

Table 5: CCS cost estimates by industry sector (USD/tonne CO₂)

Industrial sector	Estimated cost range (USD/tonne CO ₂)	CO ₂ emission typology	Main observations
Bioethanol production	25–40	High concentration	Relatively pure CO ₂ stream, low costs
Ammonia production	30–50	Constant and concentrated flow	Economically feasible application
Electricity (coal)	55–110	Diluted emissions, continuous flow	Requires major adaptations
Electricity (gas)	75–120	More diluted emissions	High costs for separation
Cement industry	80–130	Complex process, diffuse emissions	Big challenges for capture and integration
Steel and metallurgy	90–150	Variable and intermittent emissions	High costs, lack of scalability

Source: data processed after Rubin, Davison, Herzog, (2015) and the IEAGHG (2020) and Global CCS Institute (2023) reports.

Table 5 provides a comparison of the estimated costs of implementing carbon capture and storage (CCS) technologies in key industrial sectors, expressed in US dollars per tonne of CO₂ captured and stored. This analysis highlights the significant economic variability across industries, influenced by the nature of the processes, the concentration of CO₂ emissions, and the feasibility

of integrating the technologies. The bioethanol and ammonia industries stand out for their lowest implementation costs, due to their relatively pure CO₂ streams and the already existing capture infrastructure, making them among the most economically viable. In contrast, sectors such as cement and metallurgy generate diffuse emissions with variations in flow and composition, leading to high capture costs and the need for complex technological adaptations. The differences between coal-fired and gas-fired power plants reflect not only the type of fuel used, but also how it affects the composition of the flue gas and the energy costs associated with the capture process. Gas-fired power plants, although less polluting in terms of gross emissions, generate higher costs per tonne captured due to the low concentration of CO₂ in the flue gases. This analysis highlights that the economic feasibility of carbon capture and storage (CCS) cannot be generalized, but must be assessed according to the technical and economic conditions specific to each sector and the available support policies.

Legislative and regulatory challenges

Legislative and regulatory challenges are one of the most significant obstacles to the large-scale deployment of carbon capture and storage (CCS) technologies. To make CCS an effective tool in combating climate change, a clear, comprehensive and harmonised legislative framework is needed that addresses risk, defines responsibilities and ensures transparency and social acceptance. This can make CCS a sustainable and viable solution for reducing global emissions. A coherent and enabling legislative framework is crucial to facilitate the uptake and deployment of CCS technologies. **Table 6** provides an overview of the main European and international regulations and relevant initiatives in support of CCS.

Table 6: Legislative framework and policies relevant to CCS technologies

Regulatory area	Example / Relevant document	Main observations
EU CCS regulations	Directive 2009/31/EC on the geological storage of CO ₂	Sets technical and safety requirements for underground CO ₂ storage
EU Green Taxonomy	Regulation (EU) 2020/852 on sustainable investment	CCS is eligible for green financing if it contributes significantly to climate change mitigation
European Climate Policies	Fit for 55 package, Green Deal	Includes CCS as part of the heavy industry decarbonization strategy
ETS Schemes	EU ETS – Emissions Trading System	CCS reduces compliance obligations for industrial operators
National Initiatives	National CCS strategies (e.g. Netherlands, Norway, United Kingdom)	Financial support programs and regulations tailored to CCS development
Cross-border Aspects	Amended London Protocol, maritime conventions	Allows cross-border transport of CO ₂ for geological storage

Source: processed data author

Carbon capture and storage (CCS) technologies are essential in global strategies to reduce greenhouse gas emissions, playing an important role in limiting global warming. However, the large-scale implementation of these technologies faces numerous legislative and regulatory obstacles, which require careful analysis and solutions to ensure the efficiency, safety and social acceptability of CCS.

a) Current legislative realities for CCS

i) *Lack of a clear and coherent legal framework.* In most countries, legislation on carbon capture and storage (CCS) is either incomplete or insufficiently detailed. Current regulations are often fragmented, addressing only certain aspects, such as project authorisation, emissions monitoring or post-injection liability.

ii) *Integration with existing environmental and energy legislation.* CCS technologies need to align with already complex legal regimes, including climate change legislation, environmental protection, subsurface exploitation and industrial safety regulations.

iii) *Lack of clear rules on ownership and liability.* A major challenge is the precise definition of ownership rights over geological storage sites and long-term legal responsibility for the integrity of CO₂ storage sites.

b) Current limits in CCS regulation

i) *Legal uncertainties related to long-term liability.* Due to the long duration that carbon dioxide must remain in underground storage (possibly hundreds or even thousands of years), current legislation does not provide adequate legal clarity regarding liability for any leakage or risks that may arise after the closure of these storages.

ii) *Obstacles in the permitting and environmental impact assessment process.* Bureaucratic permitting processes are often slow and complicated, which can delay the implementation of carbon capture and storage (CCS) projects. Environmental impact assessments also need to be adapted to include the specific risks associated with CCS, such as CO₂ leakage.

iii) *Lack of uniform technical and monitoring standards.* There is no unified set of standards for monitoring, reporting and verification (MRV) of the quantities of CO₂ captured and stored, which makes it difficult to compare and trace projects.

c) Legislative and regulatory development perspectives and directions

i) *Creating an integrated and flexible regulatory framework.* It is essential to develop clear and adaptable legislation that covers all stages of the life cycle of carbon capture and storage (CCS) projects, from capture and transport, to storage, post-injection monitoring and closure of storage facilities.

ii) *Establishing a clear post-closure liability and financing regime.* Future legislation should include precise mechanisms for transferring liability from operators to the state or other entities after the closure of storage facilities, as well as guarantee funds for unforeseen risks.

iii) *Developing internationally harmonised standards and procedures.* International collaboration is essential for standardising rules on monitoring, reporting and verification (MRV), risk assessment and good practices in CCS implementation, thus facilitating access to carbon markets and green financing.

iv) *Public involvement and transparency in decision-making processes.* Legislation should encourage public consultation and access to information, thus contributing to increasing social acceptability and trust in CCS technologies.

Conclusions

The implementation of carbon capture and storage (CCS) technologies is a key component in the global transition towards climate neutrality, especially in industrial sectors that are harder to decarbonize. The analysis carried out in this paper has highlighted a number of relevant conclusions, organised according to the main dimensions investigated. First, CCS technologies are

based on well-established scientific principles and have reached a mature technological stage for certain applications, such as post-combustion amine capture and geological storage in saline reservoirs. However, energy efficiency and technological flexibility vary significantly depending on the type of capture used, as demonstrated by the energy penalties associated with each technology.

Second, the cost analysis has shown that the implementation of CCS requires a considerable economic effort, both in terms of capital investment and operational costs. Although there are significant differences between industries and technologies, the general trend suggests a possible reduction in costs in the future, thanks to technological innovations and continued political support.

In terms of opportunities and limitations, CCS offers significant advantages in reducing CO₂ emissions, particularly for the power, steel and petrochemical sectors. However, challenges related to the availability of storage sites, uncertainties regarding social acceptance and the absence of a dedicated market for captured carbon constitute significant obstacles.

International regulatory frameworks and policies play a key role in promoting the development of carbon capture and storage (CCS) technologies. European regulations, together with emerging national strategies, contribute to creating a favourable environment for investment. However, closer coordination between the different institutional levels and an acceleration of the effective implementation of these measures are needed.

In conclusion, the long-term success of CCS technologies depends on strengthening the technical, economic and institutional foundations. Their coherent integration into national and European climate policies, together with an active involvement of industry and communities, will determine the extent to which CCS can become a scalable and sustainable solution to achieving decarbonisation goals.

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