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SOCIETAL IMPACT

of CNRS research
on CO₂ capture, utilisation
and storage



Publication management
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EXECUTIVE summary

OBJECTIVES

The objective of this impact study is to review the research conducted by the CNRS and its partners¹ on the capture, utilisation and storage of CO₂ produced by industrial activities (CCUS), and to analyse its effects on society across economic, political and regulatory, environmental, social, cultural, and health dimensions.

The study aims to understand how scientific knowledge is disseminated to industrial, political, financial, and societal stakeholders, and how this knowledge may foster disruptive innovations and contribute to the emergence of a structured CCUS sector. It also examines the conditions under which such knowledge can influence industrial decarbonisation strategies and provide objective input to public debates on reducing carbon emissions. Finally, the study seeks to identify key levers for enhancing the future societal impacts of CCUS, as well as for improving the coordination between research, technological development, industrial deployment, and public policy in this field.

1. Most research conducted by the CNRS is carried out within laboratories established through partnerships with other academic institutions, predominantly universities. Accordingly, any reference in this study to “CNRS research” encompasses both the CNRS and its partner institutions.

METHODOLOGY

The impact study was conducted between November 2025 to March 2026 and is structured around three main stages:

1

DEFINING THE TIMELINE of scientific research and technological innovations in the field of CCUS over the past twenty years (2005—2025) **(Deliverable on pages 10-11);**

2

ANALYZING THE STAGES OF THE IMPACT PATHWAY, i.e. the progression of knowledge from its production to its effects on society. This includes the resources mobilised for research ('Inputs'), the scientific results ('Outputs'), the actors who appropriate and transform these results ('Intermediaries') and the societal effects generated ('Impacts') **(Deliverable on pages 12-13);**

3

DEVELOPING AN IMPACT RADAR TO MAP SOCIETAL EFFECTS across multiple dimensions: economic, political and regulatory, environmental, social, cultural, and health **(Deliverable on page 8).**



This methodology is based on a comprehensive review of scientific and technical literature, as well as media, economic, and policy sources. It also draws on the analysis of bibliometric and patent databases, and on 25 semi-structured interviews conducted with scientists, public and institutional officials, industry representatives, start-up executives, investors, and civil society actors.

This document has been reviewed and revised by the stakeholders involved in the consultation process.

MAIN FINDINGS

Since 2005, research on CCUS has expanded significantly, driven by increasing climate constraints, the pursuit of carbon neutrality, and the need to address hard-to-abate industrial CO₂ emissions.

However, it took more than fifteen years for a clear policy position on CCUS to emerge in France and across Europe. This prolonged period of uncertainty slowed the development of industrial roadmaps, technological innovation, and the structuring of the scientific community.

Despite this context, the CNRS and its partners have come to play a major role within the French ecosystem. The scientific community in this field now includes around 35 research units (either UMRs—*Unité Mixte de Recherche*— or UPRs—*Unité Propre de Recherche*—) and approximately 340 full-time equivalents (FTEs), compared with about 50 FTEs in 2005. Their work has generated significant advances across multiple segments of the value chain, including improvements in capture processes, development of new adsorbents and porous materials, progress in electro- and photo-catalysis for CO₂ conversion, advances in mineralization and geological storage, enhanced monitoring and life-cycle analysis of the entire chain, and increased understanding of the social acceptability of CCUS. Research priorities have also evolved markedly: while capture and storage dominated the period from 2005 to 2015, CO₂ utilisation has become the main focus of CNRS research since the early 2020s.

While the CNRS appears particularly well positioned in fundamental research, the study highlights a key structural feature of the field: CCUS has not historically developed as an integrated field of research. Instead, it has evolved as two relatively independent domains—CCS and CCU (for CO₂ storage and utilisation respectively)—each comprising fragmented scientific communities working on distinct segments and technologies, with limited coordination across the value chain. In this context, the launch of the PEPR SPLEEN program in 2023 represents a significant turning point. It contributes to structuring the field by fostering collaboration between laboratories on process decarbonisation, CO₂ storage and utilisation, while also supporting the development of crosscutting modelling and monitoring tools. ■■■

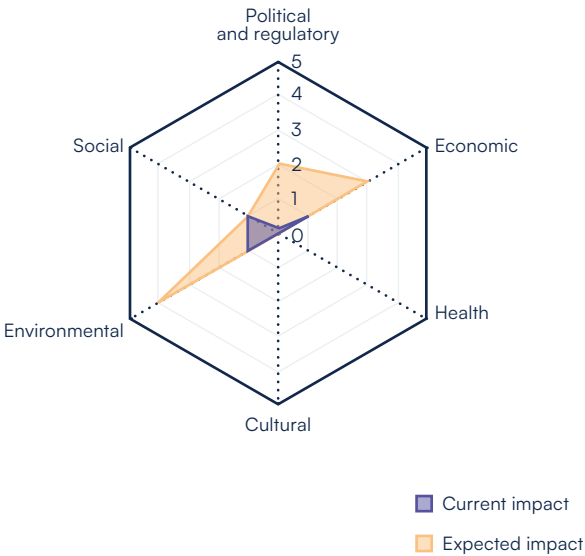
■ ■ ■ However, this structuring effort remains partial: primarily focused on fundamental research, this program alone cannot fully address key challenges such as technological maturity (partly supported by initiatives such as the CACTUS program led by CNRS Innovation and the SATT Pulsalys), process integration, industrial-scale deployment, and the development of partnerships between spin-offs and large industrial groups. Addressing these challenges could now form the basis for targeted strategic action by the CNRS and its partners.

This fragmentation underscores the critical role of intermediaries, i.e. actors capable of translating scientific results into solutions that can be deployed at technical, economic, and industrial scales. In the field of CCUS, this transformation involves a wide range of stakeholders, including organizations such as IFPEN, start-ups, large industrial groups engaged in decarbonisation, investors, and participants in public and policy debates. The transition from research to large-scale applications is reflected in various forms of technology transfer, including collaborative research projects with industry, joint chairs and laboratories, maturation programs, patenting activities, and the creation of start-ups. While these dynamics point to strong innovation potential in CCUS, they remain insufficient to meet industrial challenges. Key limitations include the shortage of pilot sites and demonstrators, as well as difficulties in ensuring continuity between upstream research, process engineering, funding for intermediate Technology Readiness Levels (TRLs), and large-scale deployment.

In this context, it is important to emphasise that no fully operational CCUS industrial sector currently exists in France. This situation significantly limits the societal impacts that can be directly attributed to CNRS research, which, for the most part, remain at an early stage and are often prospective rather than realised. Nevertheless, this research plays a crucial role in informing future technological choices, structuring the emerging sector, and clarifying the economic, political, and social conditions required for its deployment.

At this stage, direct **economic impacts** remain limited. Revenue from patents is still modest, and tangible effects are primarily observed through the creation of start-ups, the development of research partnerships, and the growing visibility of the field. The principal contribution of research therefore lies less in immediate economic returns than in its capacity to generate innovations that may underpin a future industrial sector.

Impact Radar



The **political and regulatory impact** appears more mixed. While research conducted by the CNRS and its partners is expected to play a decisive role in improving the efficiency, cost-effectiveness, and control of CO₂ capture, utilisation, and storage processes, scientific stakeholders remain under-represented in national strategic planning bodies. The study highlights, for example, that the first national steering committee dedicated to CCUS, which met in February 2026, did not include scientific representatives. This reveals a disconnection between the expertise available within research laboratories and its mobilization by public authorities to inform strategic decisions and support evidence-based public debate on the role of CCUS in decarbonisation pathways.

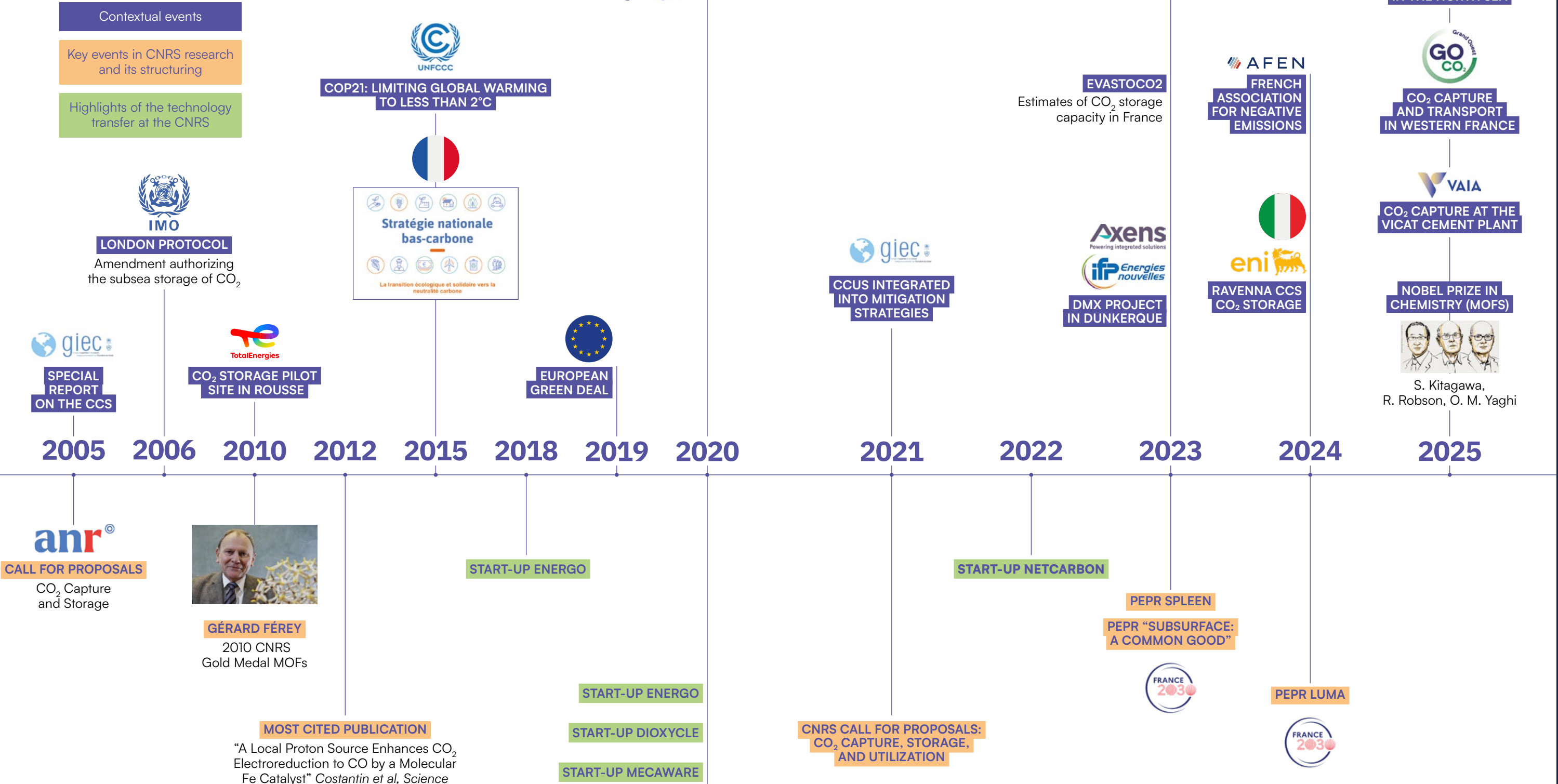
The **environmental impact** is potentially substantial but remains contingent on the effective deployment of the sector. Research is already contributing to the development of more efficient capture and utilisation technologies, as well as to the monitoring and life cycle assessment tools required to evaluate the overall performance of CCUS systems. However, the associated environmental benefits remain largely prospective until complete value chains—encompassing capture, transport, utilisation, and storage—are implemented at industrial scale.

The **social impact** is, at this stage, more indirect. While employment prospects by 2050 are expected to be significant, the immediate effects of the research relate primarily to training, skills development in emerging technologies, and the potential contribution of CCUS to maintaining existing industrial activities or supporting their transition towards more sustainable production methods in high-emission sectors. Social impact also arises from the capacity of research to clarify the conditions under which industrial and environmental objectives can be reconciled in support of the ecological transition.

Finally, within the scope of this study, **cultural and health impacts** are less directly observable at present.

In conclusion, this study reveals a pronounced disparity between the excellence of French research—particularly that conducted by the CNRS and its academic partners—and an industrial sector that remains nascent, economically fragile, and historically constrained by political and regulatory hesitations. The CNRS plays a pivotal role in addressing upstream scientific challenges, enabling certain disruptive innovations, and, to some extent, fostering objectivity in public and policy debates. To strengthen future societal impacts, several key levers emerge: the development of pilot projects and demonstrators for emerging technologies; closer integration of chemistry, process engineering, and geosciences; more systematic involvement of the humanities and social sciences in analysing public discourse, perceptions, and issues of adoption and acceptability; and a more explicit incorporation of scientific expertise into the formulation of public policy.

TIMELINE



IMPACT PATHWAY

CONTEXT

Need for carbon
neutrality and industrial
competitiveness

- 1

REDUCE “HARD-TO-ABATE” CO₂ EMISSIONS
- 2

INCREASE CO₂ CAPTURE

MOBILIZATION OF SCIENTISTS

- More than 35 laboratories (UMR and UPR) involved in all areas of CCUS, including one international laboratory
- More than 3,550 cumulative FTEs from 2005 to 2024 (including more than 1,020 CNRS FTEs)
- €258 million in payroll (including €75 million CNRS)

SCIENTIFIC NETWORKS AND PARTNERSHIPS

- PEPR programs: SPLEEN, Subsurface and LUMA to a lesser extent
- European infrastructure ECCSEL (ERIC)
- 14 CNRS-industry partnership contracts

FUNDING

- €140 million from 2005 to 2025 (excluding payroll costs), including €32 million from CNRS
- Sources: ANR, PEPR, Europe, CACTUS program for pre-maturation and maturation, CNRS-industry partnerships...

INPUT

SCIENTIFIC PRODUCTION

- Leading-edge scientific advances in MOFs, electrochemical processes, CO₂, catalysis, characterization of storage reservoirs, and analysis of social acceptance
- Nearly 2,300 French publications since 2005 (including 1,250 with CNRS authors)

PATENTS AND VALUABLE KNOW-HOW

- Exploitation of inventions related to MOFs and CO₂ reduction...
- 73 families of inventions filed by the CNRS since 2005, including 11 with licensing agreements

INNOVATION AND ENTREPRENEURIAL DYNAMICS

- 8 startups founded or supported by the CNRS (Mecaware, Energo, NetCarbon, Dioxcycle, Carboneo...)
- 2 early-stage projects and 20 mature projects supported by the CNRS (support from CNRS Innovation, the France 2030 CACTUS program, technology transfer offices...)
- 8 Joint Laboratories and Industry Chairs
- 2 Carnot Institutes

TRAINING

- Continuing education
- More than 110 theses on CCUS in France

OUTPUT

● Outputs that fed into the intermediaries

NATIONAL AND EUROPEAN POLITICAL INSTITUTIONS

- Proactive policies despite several years of stop-and-go progress
- Incentive-based regulations
- National public policies insufficiently grounded in scientific evidence

PUBLIC AND PRIVATE INVESTORS

CO₂-EMITTING INDUSTRIES

INDUSTRIAL STAKEHOLDERS IN THE CCS AND CCU VALUE CHAINS

- Ongoing structuring of the value chains
- Established technologies
- No breakthrough innovation, but identified needs for scientific input

TECHNOLOGICAL INNOVATORS

ADVISORY AND INFLUENCE STRUCTURES

- Role of the CO₂ Club, bringing together economic and scientific stakeholders

ACTORS IN THE PUBLIC DEBATE

- Role of the CNDP in several CCUS-related projects
- Constructive dialogs with associations and think tanks

TRAINING INSTITUTIONS

MEDIA

- Around 1,000 documents identified between 2005 and 2025, including 500 in the French-speaking press
- Growing media interest linked to environmental and industrial challenges

INTERMEDIARIES

SCIENTIFIC IMPACT

- Still limited structuring of the scientific community and dialogue with other stakeholders
- New scientific questions arising from the current and future development of the CCUS value chain

ECONOMIC IMPACT

- Modest economic impact to date, but expected to grow as a result of recent political and industrial decisions to develop the value chain
- Lack of pilots and demonstrators to accelerate TRL increase and the industrialisation of disruptive innovations
- Emerging CNRS startups

ENVIRONMENTAL IMPACT

- Development of resource-efficient technologies in response to the challenges of reducing energy costs, promoting sustainability, mitigating risks, and securing resources

POLITICAL AND REGULATORY IMPACT

- France makes limited use of its researchers to define its national CCUS strategy and prepare for the future

SOCIAL IMPACT

- Job creation through startups originating from CNRS
- Training of qualified personnel through research
- Role of intermediary bodies in fostering public understanding and appropriation of CCUS

IMPACTS

INITIAL external context

The concept of CCUS—encompassing carbon capture, utilisation, and storage—has only recently emerged as a structured field of research and technological development. It is, however, rooted in a much longer scientific and political trajectory associated with the understanding of the greenhouse effect and efforts to mitigate climate change.

As early as the late nineteenth century, the Swedish chemist Svante A. Arrhenius (Nobel Prize in Chemistry, 1903), building on the foundational work of Fourier, de Saussure, Newton, and Tyndall, identified the greenhouse effect and underscored the central role of CO₂ in the Earth's thermodynamic balance. Throughout the twentieth century, the study of greenhouse gases and their influence on the global climate continued to advance. Yet it was not until the 1980s that this body of knowledge translated into coordinated international political action. The 1987 Montreal Protocol, established under the auspices of the United Nations Environment

Program, marked a significant milestone by formalizing global commitments to protect the ozone layer. This momentum was further reinforced at the 1992 Earth Summit in Rio, which set international objectives for stabilising emissions of major greenhouse gases, including CO₂, CH₄, N₂O, HFCs, PFCs, and SF₆.

The need to reduce effectively greenhouse gas emissions became a central issue with the adoption of the Kyoto Protocol at COP3 in 1997, supported by successive IPCC assessments. From the early 2000s onwards, the concept of carbon neutrality progressively

emerged, incorporating the offsetting of unavoidable emissions. This trajectory culminated at COP21 in 2015, with political commitments to achieve carbon neutrality within varying timeframes depending on the country (e.g., 2050 in Europe and 2060 in China).

To reach carbon neutrality and limit global warming to 1.5°C, several pathways—particularly those proposed by the IPCC—define key objectives: phasing out fossil fuels, reducing energy demand through conservation and efficiency improvements, and decarbonizing major sectors such as energy, transport, and industry. For sectors where low-carbon alternatives remain limited in the medium term, these scenarios emphasize the deployment of carbon capture technologies. Captured CO₂ can either be permanently stored in geological formations such as saline aquifers, depleted oil and gas reservoirs, or mafic and ultramafic rocks (referred to as CCS, for carbon capture and storage), or reused as a feedstock in the production of fuels, chemicals, construction materials, or in agri-food applications (e.g., beverage carbonation), referred to as CCU for carbon capture and utilisation. The broader CCUS value chain also includes the transport of CO₂ from capture sites to storage or utilisation locations, as well as significant economic, technological, scientific, and societal acceptance challenges. According to the European Commission, CCUS will play a critical role in mitigating emissions, with targets of approximately 280 million metric tons of CO₂ per year (MtCO₂/year) in Europe by 2040 and around 450 MtCO₂/year by 2050. In France, the National Low-Carbon Strategy (SNBC), introduced in 2015 and updated in 2024, provides a structured political, scientific, and industrial

framework for CCUS deployment, setting a target of 4 to 8 MtCO₂/year captured by 2030, followed by a progressive scale-up toward 2050.

CCUS is based on a technological—and ultimately commercial—value chain that, although relatively short, encompasses a wide range of processes. Its key stages include CO₂ capture, purification, concentration and, where necessary, liquefaction, followed by transport, and finally either storage (CCS) or utilisation (CCU). Each stage relies on specific technologies, and the overall effectiveness of the sector depends on their coordinated development. Industrial stakeholders are actively engaged across this value chain, working to scale up and optimize the processes under their responsibility.



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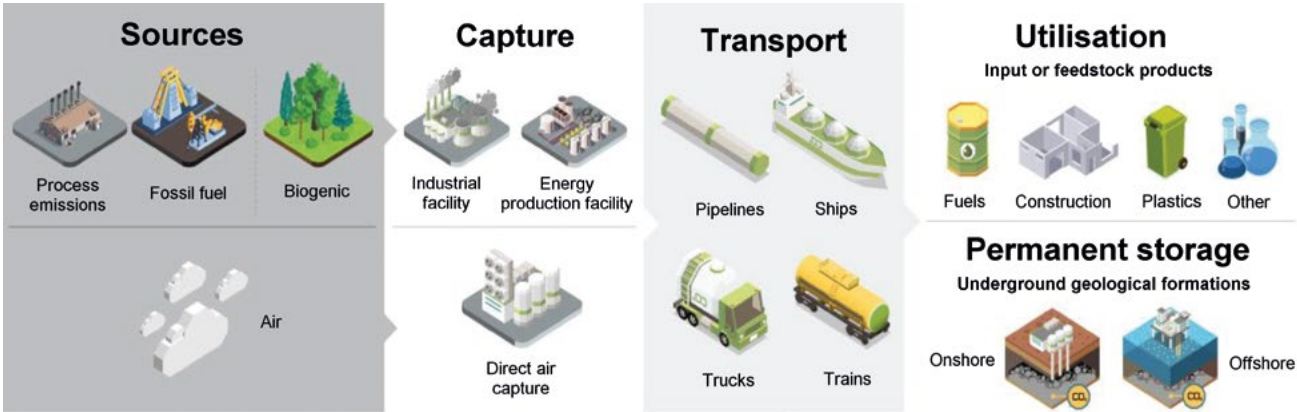
Importantly, CCUS does not rely on fundamentally new technologies. CO₂ capture and separation processes have been employed in industry for several decades. Likewise, the transport and injection of CO₂ into the subsurface have been practiced since the 1970s, primarily in the context of enhanced oil recovery (EOR), particularly in the United States. In addition, some industrial sectors, such as the food and beverage industry, already use CO₂ as a raw material, albeit at relatively limited scales. However, meeting greenhouse gas emission reduction targets will require the rapid development of a fully integrated CCUS industrial sector. This transition entails the deployment of high-capacity capture facilities, the large-scale expansion of transport infrastructure, the development of extensive storage capacities, and the emergence of a significant industrial sector dedicated to CO₂ utilisation, particularly for the production of synthetic fuels and other high-value-added products.



Meeting greenhouse gas emission reduction targets will require the rapid development of a fully integrated CCUS industrial sector.

Figure 1: Overview of the CCUS value chain, from CO₂ emission sources to utilisation (CCU) and storage (CCS), including capture and transport processes

(sources: PEPR SPLEEN and the European Commission)



CCUS spans a broad and multidisciplinary set of scientific domains—including catalysis, electrochemistry, thermodynamics, fluid mechanics, geology, and the social sciences—and covers the full range of Technology Readiness Levels (TRLs), from fundamental research to industrial deployment. The processes involved are equally diverse (see Figure 1): CO₂ capture from industrial flue gases, biomass, or directly from the atmosphere; transport via pipelines, road, rail, or maritime routes; various utilisation pathways including direct use, biological, chemical, and mineral conversion, as well as the production of e-fuels and polymers; storage in both offshore and onshore sites, such as depleted hydrocarbon reservoirs, saline aquifers, and mafic or ultramafic formations. As a result, the CCUS sector brings together a wide range of scientific, industrial, and policy stakeholders, operating across different institutional, cultural, and geographical contexts, and often pursuing distinct or even competing objectives. In light of this complexity, the present study deliberately focuses on CO₂ capture from industrial and energy-related sources, while direct air capture is addressed only marginally.

Beyond providing an overview of CCUS research conducted at the CNRS and by its partners since 2005, this study examines its impacts across multiple dimensions: economic, political and regulatory, environmental, social, cultural, and health. The objective is to better understand how scientific knowledge is produced, disseminated, and interpreted by various stakeholders to generate societal outcomes, as well as how societal needs and challenges can, in turn, influence the direction of scientific research.



INPUT and contributions from the CNRS and its partners

BACKGROUND OF THE RESEARCH FIELD

Within the scientific and political context outlined in the previous section, the technologies now grouped under the acronym CCUS are rooted in a long history of industrial and scientific developments that predate their explicit application to climate change mitigation.

CO₂ utilisation processes constitute one of the historical background of this field. The Sabatier process, based on the thermocatalytic hydrogenation of CO₂, was developed as early as 1897 and contributed to the award of the Nobel Prize in Chemistry in 1912 to Paul Sabatier. The Fischer—Tropsch process, developed in Germany from 1923 onwards, was later used by the Nazi regime to ensure a relative degree of energy self-sufficiency: it enables the synthesis of hydrocarbons from carbon monoxide and hydrogen

via heterogeneous catalysis, according to the chemical reaction $(2n+1) \text{H}_2 + n \text{CO} \rightarrow \text{C}_n \text{H}_{2n+2} + n \text{H}_2 \text{O}$. Carbon monoxide required for this process can be produced from CO₂ via the Reverse Water—Gas Shift (RWGS) reaction: $\text{CO}_2 + \text{H}_2 \rightarrow \text{CO} + \text{H}_2\text{O}$. These processes remain key reference points for the CCU sector today, both scientifically and industrially.



Research on CO₂ capture, storage, and utilisation remained relatively marginal for much of the 20th century. A significant resurgence of interest emerged only in the early 2000s, both in France and internationally, driven by the growing imperative of achieving carbon neutrality.

Starting in the second half of the 20th century, major advances in electrochemistry, molecular chemistry, and catalysis complemented these pioneering developments. In France, research conducted between 1985 and 2000 by leading scientists such as Jean-Marie Lehn (CNRS Gold Medal in 1981 and Nobel Prize in Chemistry in 1987), Jean-Pierre Sauvage (Nobel Prize in Chemistry in 2016), and Jean-Michel Savéant laid the groundwork for molecular catalysis based on transition metals. This work has since played a central role in the renewed interest in CO₂ conversion processes.

In parallel, CO₂ capture and storage technologies started to develop into industrial applications as early as the first half of the 20th century. CO₂ was captured primarily to purify methane in natural gas processing, but also for use in applications such as beverage carbonation and urea production. At that time, capture technologies relied predominantly on chemical absorption using amine-based solvents. From the 1970s onwards, industries—particularly in the United States—developed the use of CO₂ for enhanced oil recovery (EOR), injecting it in a supercritical state into oil reservoirs to increase extraction yields.

The modern concept of carbon capture and storage (CCS), explicitly aimed at reducing CO₂ emissions, was first proposed by Cesare Marchetti in the late 1970s. The Sleipner project, initiated in 1996, followed by the IEA Greenhouse Gas R&D Programme's Weyburn project in 2000, marked the first large-scale international demonstrations of the capture, utilisation, and storage of anthropogenic CO₂ emissions².

Despite being grounded in long-established scientific and technological principles, research on CO₂ capture, storage, and utilisation remained relatively marginal for much of the 20th century. A significant resurgence of interest emerged only in the early 2000s, both in France and internationally, driven by the growing imperative of achieving carbon neutrality. Building on advances in chemistry, geology, and social sciences, CCUS has progressively become both a subject of scientific investigation and a component of public and policy debate. It is now widely regarded as a complementary—yet essential—lever in decarbonisation strategies, particularly for industrial sectors with 'hard to abate CO₂ emissions'. In this context, CCUS brings together previously disconnected scientific and technological domains to address persistent sources of CO₂ emissions.

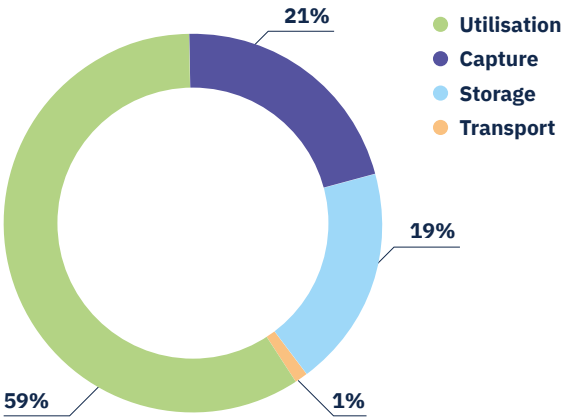
2. See "Carbon Capture and Storage: History and the Road Ahead", Engineering 14:33–43 (2022), <https://doi.org/10.1016/j.eng.2021.11.024>

RESEARCH STRUCTURE IN FRANCE
AND AT THE CNRS

At present, **around 35 joint research units (UMRs and UPRs)³, operating under the supervision of the CNRS and its academic partners**, are significantly engaged in research on CO₂ capture, storage, or utilisation (see Appendix 2 for the distribution of laboratories across the four CCUS domains). In 2024, these laboratories represented approximately 340 full-time equivalent (FTE) positions. Cumulative **data for the period 2005–2024 indicate a total of 3,565 FTEs involved in CCUS-related research across all roles and career stages**, including 1,022 funded by the CNRS. Over this period, **the total associated payroll reached €258.5 million**, of which €75 million was attributable to the CNRS (see Appendix 1).

This period is marked by a steady increase in scientific engagement in CCUS, with the workforce growing from around 50 FTEs in 2005 to more than 300 FTEs from 2023 onwards. The distribution of research efforts across CCUS domains has also evolved significantly. In 2016, only 12% of FTEs were dedicated to CO₂ utilisation but it rose to 38% in 2019 and reached 59% in 2024. Currently, nearly 60% of researchers are working on various CO₂ utilisation pathways, while capture and separation, on the one hand, and storage, on the other, each account for approximately 20% of the workforce. Finally, CO₂ transport is only marginally represented in fundamental research activities.

Figure 2: Distribution of FTEs across the different CCUS domains.



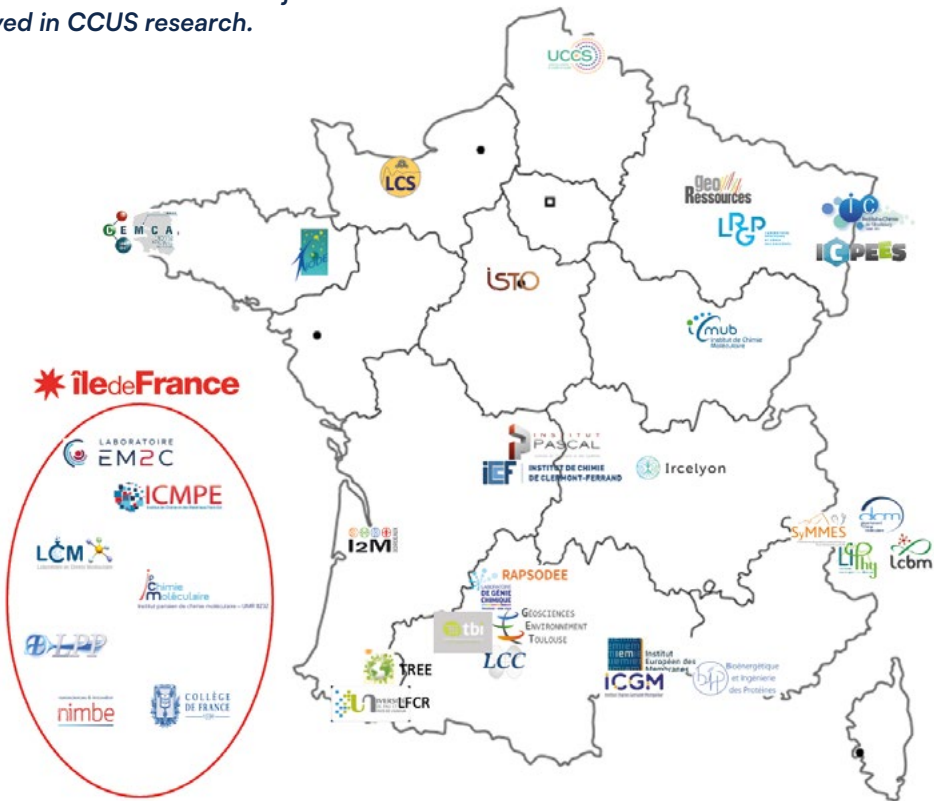
3. This figure includes only research units with at least 4 FTEs dedicated to CCUS sector.



The laboratories involved in CCUS research are distributed across the entire country, as illustrated in Figure 3. Several regional clusters stand out for their level of activity, notably in the South-West (Toulouse, Pau, Albi), the East (Nancy, Strasbourg), the Auvergne—Rhône-Alpes region (Grenoble, Lyon, Clermont-Ferrand), and the Île-de-France region. In addition to these France-based laboratories, CCUS research also benefits from international collaborations. Notably, the International Research Laboratory (IRL) Eco-Efficient Products and Processes Laboratory (E2P2L), located in Shanghai, brings together the CNRS and Syensqo (formerly Solvay), in partnership with the École Normale Supérieure de Lyon, the Universities of Lille and Poitiers, and several Chinese institutions, including ECNU (East China Normal University), ECUST (East China

University of Science and Technology), and Fudan University. This laboratory focuses on renewable and sustainable chemistry, with a particular emphasis on CO₂ utilisation. Furthermore, an International Research Project (IRP) has supported sustained collaboration between IRCELYON and the team led by Suzumu Kitagawa (Nobel Prize 2025) at the University of Tokyo, in association with Air Liquide. This partnership focuses on metal—organic frameworks (MOFs), which are of particular interest for CO₂ capture and separation.

Figure 3: Geographical distribution of CNRS joint research units involved in CCUS research.



The CCUS sector does not correspond to a single, clearly delineated scientific field, but rather draws on a diverse set of laboratories with expertise spanning CO₂ capture, utilisation and storage, often alongside other research areas. Until recently, the scientific community had not been formally structured around CCUS as a unified domain. This began to change with the launch of the PEPR SPLEEN program (2023–2030), part of the national strategy to accelerate industrial decarbonisation. Two of its main research areas—“Process Decarbonisation” and “CO₂ Utilisation and Storage”—aim to strengthen collaboration among relevant laboratories and support the development of upstream research activities (TRL 1–4), while the transverse axis “New Prediction and Monitoring Tools” seeks to provide common tools that are also directly relevant to the CCUS sector.

Other initiatives further contribute to structuring this field in France. In particular, the Synflux-Lumicals project, supported by the PEPR LUMA (Light—Matter Interactions), focuses on developing innovative approaches to collecting and utilising light more efficiently in solar fuel production systems, notably by enhancing the efficiency and selectivity of photo-, electro-, and photoelectrochemical CO₂ conversion processes. In parallel, the AQUIBEAT project, part of the PEPR “Subsurface: a common good”, aims to advance geological knowledge of the Aquitaine Basin in support of the energy transition, with a specific focus on CO₂ storage.

Although French academic research on CCUS has long appeared relatively fragmented, European research infrastructure dedicated to CO₂ capture, transport, storage, and utilisation has been consolidated since

2017 within the European Research Infrastructure Consortium ECCSEL (European Carbon Dioxide Capture and Storage Laboratory Infrastructure), which also encompasses as atmospheric CO₂ capture, geothermal energy exploitation, and underground energy storage. Positioned at the interface between academic research and pre-industrial applications, the network primarily supports research and demonstration activities. The French node of ECCSEL, coordinated by BRGM, brings together a range of infrastructures operated by public research organisations—including BRGM, IFPEN, INERIS, Andra, CNRS, and ARMINES—as well as major industrial stakeholders such as EDF, TotalEnergies, and Lafarge Holcim France. This configuration reflects a strong integration of scientific and industrial capabilities at the national level. In parallel, the SUNERGY initiative represents a broader pan-European effort to promote a circular carbon economy. Its objective is to enable the sustainable production of fossil-free fuels and base chemicals using renewable energy sources (such as solar and wind) and widely available molecules, including CO₂, water, and nitrogen. Bringing together around 30 organisations across 12 countries—from industry, academia (including the CNRS), and civil society—SUNERGY aims to develop a shared technological roadmap, foster a portfolio of European projects, and lay the groundwork for a large-scale research and innovation initiative.

FUNDING

A wide range of public funding sources, including CNRS internal funding as well as regional, national, and European programs has supported research on CCUS in France, particularly within CNRS laboratories. Given their diversity and volume, regional funding schemes are not detailed here.

Since 2012, the CNRS has allocated approximately **€17 million** in “FEI” (Operating, Equipment, and Investment) funding to laboratories engaged in CCUS research. An extrapolation based on full-time equivalent (FTE) staffing levels between 2005 and 2011 suggests that an additional **€4.4 million** was provided during this earlier period. Overall, CNRS FEI funding for CCUS research is therefore estimated at **€21.4 million** over a 20-year period. At the national level, funding for CCUS-related projects involving CNRS laboratories has been primarily provided by the ANR. This support has been delivered through generic calls for proposals (AAPG), as well as through major investment programs such as the ‘Programme d’Investissements d’Avenir’ (PIA) and, more recently, France 2030 (source: ANR). Between 2005, when the ANR was established, and 2024, a total of 65 projects involving at least one CNRS joint research unit (UMR) were funded through AAPG calls, representing **€20.24 million** allocated to CNRS-supervised laboratories. These projects include both public—public and public—private collaborations. In addition, targeted national programs have provided

significant support. Within the PEPR SPLEEN program, the “Decarbonisation of Processes” and “CO₂ Storage and Utilisation” themes have received a combined budget of **€34.3 million**. The Synflux-Lumicals project, funded under the PEPR LUMA program, has been allocated **€3.48 million**.

Technology pre-maturation and maturation projects, corresponding to Technology Readiness Levels (TRLs) 1 to 6, are currently supported under the France 2030 “CACTUS” scheme. This initiative brings together a consortium of 18 partners led by CNRS Innovation and SATT Pulsalys, and is aligned with the thematic priorities of the PEPR SPLEEN program. Since 2005, technology transfer companies (SATTs) have funded 20 maturation projects, representing a total investment of **€4.64 million**. In addition, the CNRS has supported two pre-maturation projects, amounting to **€0.275 million**.

At the European level, the European Research Council (ERC) has funded eight CCUS projects led by researchers from CNRS joint research units (UMRs), for a total of **€13.25 million**. These include one Starting Grant (2018), two Consolidator Grants (2016 and 2018), three Advanced Grants (2015, 2019, and 2020), and two Proof of Concept grants (2022 and 2024). However, the majority of European funding has been secured through collaborative projects under successive Framework Programs, from FP5 to Horizon Europe. Between 2005 and 2024, 42 such projects involving CNRS have been funded. Altogether, these European initiatives represent **€27.32 million** in funding managed by the CNRS (source: CORDIS).

The table on page 27 provides a summary of the secured funding.



The scientific community had not been formally structured around CCUS as a unified domain. This began to change with the launch of the PEPR SPLEEN program (2023–2030), part of the national strategy to accelerate industrial decarbonation.

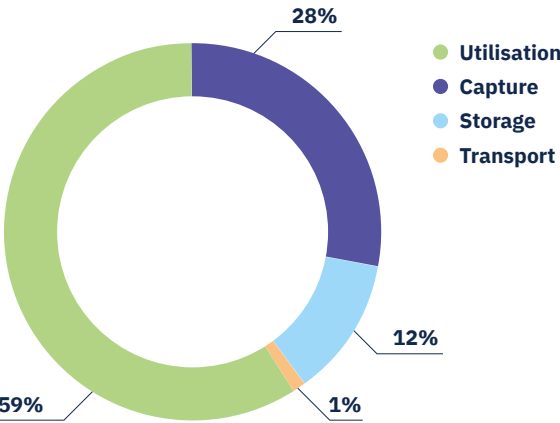
CNRS-INDUSTRY PARTNERSHIPS

Partnerships between the CNRS and industry in the CCUS sector remain relatively limited, given the significant technological and economic challenges associated with decarbonisation. Based on available data for the period from 2013 to September 2025, a total of 114 CNRS—industry partnership contracts were recorded, corresponding to an average of fewer than ten contracts per year. The total value of these contracts amounts to **€14.8 million** for the CNRS and its partner institutions, including **€5.9 million** in industrial contributions. As some contracts are signed under the joint supervision of CNRS joint research units (UMRs), the actual number of distinct partnerships is likely underestimated. According to estimates from the CNRS Business Relations Department (DRE),

the real figure may be approximately twice as high, corresponding to around twenty contracts per year and a cumulative total of about 250 partnerships over the period considered.

The distribution of these contracts across CCUS segments reveals a clear predominance of CO₂ utilisation, which accounts for nearly 60% of all partnerships. This is followed by CO₂ capture (approximately 30%) and storage (just over 10%), while transport activities remain marginal (see Figure 4). This distribution closely reflects the allocation of full-time equivalent (FTE) personnel across CCUS domains (Figure 2), although the imbalance between capture and storage appears slightly more pronounced in partnership activities.

Figure 4: Distribution of CNRS-industry partnerships across CCUS domains.



The contracts encompass a variety of arrangements, including research collaboration agreements, service agreements, consortium agreements, and CIFRE contracts. Among the 114 partnerships identified, research collaboration agreements and confidentiality agreements are the most prevalent, with more than 40 contracts in each category. As illustrated in the figure below, nearly half of these partnerships involve large companies (LCs). Small and medium-sized enterprises (SMEs) are also represented, whereas intermediate-sized companies (ISCs) remain marginal. Among large industrial partners, TotalEnergies stands out as the most frequently involved company. It is followed by other major groups in the energy sector (EDF, Orano), the chemicals industry (Air Liquide, Rhodia & Solvay, Arkema), the materials and construction sector (Holcim, Vicat, Saint-Gobain), as well as companies from more specialized industrial domains such as Naval Group.



Partnerships between the CNRS and industry in the CCUS sector remain relatively limited, given the significant technological and economic challenges associated with decarbonisation.

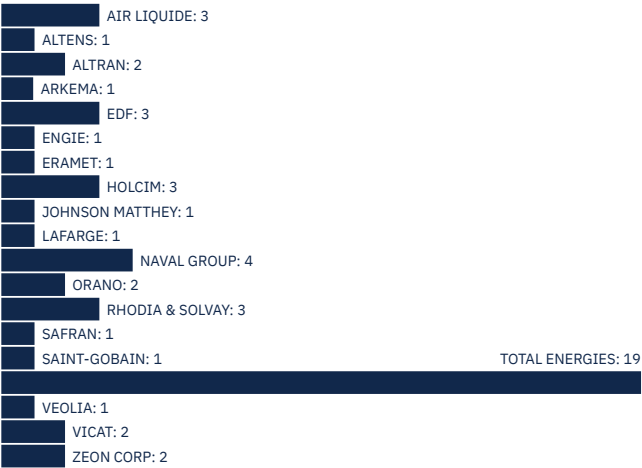
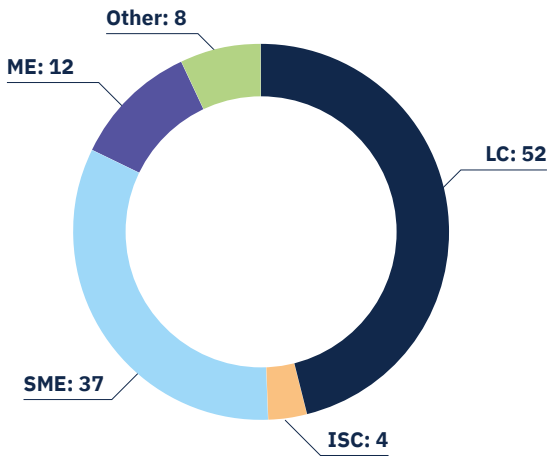


Figure 5: Breakdown of CNRS-industry partnerships (left) and main large-company partners (right).

LC = Large companies; ISC = Intermediate-sized companies; SME = Small and medium-sized companies; ME = Micro-enterprises

Finally, since 2011, eight joint laboratories (LabCom) and industrial chairs have been established between the CNRS and industrial partners in areas related to CCUS. These initiatives address a broad range of topics, including process development, life-cycle assessment, and value chain analysis. They represent the most advanced form of public—private partnership, based on jointly defined and managed scientific programs.

LabCom:

ACRONYM	YEAR OF CREATION	ACTIVE	CCUS AREA	LABORATORIES	COMPANIES
Melusine 2	2022	Yes	C	LRGP	EDF
PIGAZ	2017	Yes	C, U	LRGP	Air Liquide
Solutec	2021	Yes	C	Rapsodee	Eco-Tec Ceram

Chairs:

ACRONYM	YEAR OF CREATION	ACTIVE	CCUS AREA	LABORATORIES	COMPANIES
Smart DigiCat	2022	Yes	U	UCCS, CRIStAL, E2P2L, Institut Chevreul, INRIA	Solvay, HORIBA, TeamCat Solutions
CO2ES	2018	Yes	S	LFCE	TotalEnergies
CARB3E	2018	No	S	CERECE	TotalEnergies
TRACE	2018	No		LSCE, LMD	Suez, Thales Alenia Space, TotalEnergies
CarMa	2019	Yes	C, S	TREE	IFPEN and TotalEnergies



CCUS research within the CNRS received approximately €400 million in funding between 2005 and 2024, of which nearly €107 million was directly contributed by the CNRS.

It is also worth noting that two Carnot Institutes—ISIFOR (UPPA, CNRS) and ICEEL (University of Lorraine, CNRS)—actively support national and international R&D projects addressing energy and environmental challenges. ISIFOR focuses on subsurface-related issues, while ICEEL is dedicated to sustainable innovation.

OVERVIEW OF TOTAL FINANCIAL INVESTMENT

Overall, CCUS research within the CNRS received approximately **€400 million in funding between 2005 and 2024, of which nearly €107 million was directly contributed by the CNRS.**

INPUT (2005-2024)	€ MILLION
Total payroll	258.5 (including 75 from CNRS)
CNRS funding	21.4
ANR	20.24
PEPR SPLEEN	34.3
PEPR LUMA (Synflux-Lumicals)	3.48
Premat	0.275 (CNRS)
Maturation	4.64 (SATT)
Europe (managed by the CNRS)	27.32
Europe ERC	13.25 (including 6.26 from CNRS)
CNRS-industry partnerships	14.8 (including 8.9 from CNRS)
IP costs (for the CNRS)	1.155
TOTAL	399
TOTAL CNRS	106.7

RESEARCH outputs

THE CNRS'S MAIN SCIENTIFIC ADVANCES IN CO₂ CAPTURE, UTILISATION AND STORAGE SINCE 2005

Since the early 21st century, research conducted by the CNRS and its partners on CO₂ capture, utilisation, and storage has expanded considerably, driven by increasing climate constraints and the growing need for industrial decarbonisation. This work has led to substantial advances across the CCUS value chain, including improvements in capture technologies, enhanced understanding of geological storage processes, and the development of innovative CO₂ utilisation pathways. The following section outlines the main scientific advances achieved in these areas since 2005.

Research into CO₂ capture processes

Three main approaches are used to treat industrial flue gases: pre-combustion, post-combustion, and oxy-combustion. Among these, post-combustion capture is currently the most mature and widely deployed technology. It typically relies on the absorption of CO₂ using amine-based solvents. Significant work by the CNRS and IFPEN has focused on improving the performance of these solvents. The most advanced systems now use phase-separating (demixing) amine formulations, which enable the formation of two liquid phases—one CO₂-rich and the other CO₂-poor—thereby reducing the energy required for solvent regeneration, which remains the main limitation of this approach. In parallel, techniques such as flue gas recirculation (FGR), which involves reinjecting part of the exhaust gas into the combustion chamber, have been developed to enhance overall capture efficiency.

While amine-based absorption remains the most general solution, research over the past two decades has increasingly explored adsorption processes using porous solid materials. These include amine-functionalized resins, activated carbons, zeolites, mesoporous silicas, and MOFs. Once saturated, these materials can be regenerated either by heating (temperature swing adsorption) or by reducing pressure (pressure swing adsorption). Such systems offer several advantages: they are modular, potentially more energy-efficient, avoid the use of corrosive liquid solvents, and rely on reusable solid adsorbents with long operational lifetimes. However, they also face important challenges, including sensitivity to moisture and flue gas impurities, sometimes limited adsorption capacity, and difficulties associated with scaling up cyclic adsorption—desorption processes.

MOFs likely represent one of the most significant recent advances in the field. Owing to their specific pore size and ultra-high porosity, these materials enable highly selective CO₂ capture, including at very low concentrations, while limiting energy penalties. Pioneering work in this area is largely attributed to Gérard Férey (Versailles University, CNRS Gold Medal 2010). More recently, major contributions have been made by Christian Serre (CNRS, ESPCI, ENS), David Farrusseng (CNRS, Lyon 1 University), and Karim Adil (IMMM, CNRS, Le Mans University), who have developed particularly efficient ultra-microporous MOFs. Initially investigated for direct air capture (DAC) applications, these materials are now also highly relevant for the purification of industrial gas streams with low CO₂ concentrations. However, their large-scale industrial deployment remains challenging, as they must combine low production costs with high stability in the presence of moisture and other contaminants typically found in industrial effluents.

New avenues for CO₂ utilisation

The utilisation of CO₂ has attracted growing interest, driven in particular by European regulatory frameworks such as the ReFuelEU Aviation regulation, which mandates the progressive incorporation of sustainable aviation fuels (SAF) into aircraft operations. CO₂ utilisation relies on well-established heterogeneous catalytic processes, notably the Sabatier reaction and the Fischer—Tropsch synthesis, which enable the conversion of CO₂ into synthetic fuels and value-added chemicals.

French research benefits from strong expertise in electrochemistry, molecular chemistry, and catalysis, building on the legacy of leading scientists such as Jean-Marie Lehn (Nobel Prize in Chemistry, 1987), Jean-Pierre Sauvage (Nobel Prize in Chemistry, 2016), Alain Deronzier, and Jean-Michel Savéant. French teams are internationally recognised for pioneering new catalytic approaches—driven by thermal, electrical, or photonic energy—and for developing systems based on abundant, non-precious metals such as iron, cobalt, and copper, alongside a deep understanding of the underlying mechanisms. Notable contributions include the work of Marc Robert (CNRS, Sorbonne Université) and Marc Fontecave (CNRS, Collège de France), who have developed innovative electrochemical and photoelectrochemical pathways for CO₂ conversion, using photocatalysis, concentrated solar energy, or tailored LED systems. However, the technological and industrial maturity of these approaches remains to be demonstrated.

Since 2023, the CEA, in collaboration with the CNRS and Paris-Saclay University, has developed a dedicated programme on e-fuel production within a circular carbon economy framework. Initially led by Thibaut Cantat and now continued by Claire Gauthier (CEA, CNRS, Paris-Saclay University), this work focuses on thermocatalytic conversion of CO₂ with dihydrogen (H₂). In parallel, research by Damien Voiry (CNRS, IEM, Montpellier), Vincent Artero (CEA, CNRS, UGA), and Ally Aukauloo (CNRS, Paris-Saclay University) explores bio-inspired catalysts, which show strong potential but remain at an early, predominantly academic stage.

Another promising pathway for CO₂ utilisation involves the production of low-carbon cement and concrete through the mineralisation of CO₂ using mining residues and ultramafic rocks, potentially enhanced by bacterial catalysis. Laboratory-scale results are encouraging and suggest the possibility of valorising substantial volumes of captured CO₂. These innovative (bio)mineralisation approaches are currently being investigated as part of the CARBIOCEM project (PEPR SPLEEN).

Key challenges across these approaches include the integration of catalysts into complete and scalable systems, while maintaining cost competitiveness for each component. In addition, both capture and utilisation technologies require a better understanding of long-term performance and stability of the various components (catalysts, electrodes, etc.) under real operating conditions. Ongoing studies aim to bridge this gap by extrapolating short-term experimental results to longer time scales.

Geological CO₂ storage and its societal implications

Geological storage of CO₂—whether in deep saline aquifers, depleted onshore or offshore hydrocarbon reservoirs, or mafic and ultramafic formations—has been extensively studied over the past decade. CO₂ injection processes are relatively well understood, benefiting from knowledge developed through enhanced oil recovery (EOR) practices implemented by industry since the 1970s. Scientific advances have primarily focused on improving the understanding of multiphase CO₂ flow, long-term dissolution in brines, and the progressive mineralisation of CO₂ into stable carbonates, particularly through serpentinisation reactions. From a technological perspective, current research emphasises the monitoring and modelling of CO₂ behaviour within geological reservoirs, drawing on approaches from geochemistry and geomechanics.

Key French actors in this field include BRGM, IFPEN, and several CNRS joint research units, notably GeoRessources (Nancy), Géosciences Environnement Toulouse, Géosciences Montpellier, and the Institut de Physique du Globe de Paris (IPGP). The latter three are particularly active in the study of mineral sequestration in mafic and ultramafic rocks, in connection with the CARBIFIX pilot site in Iceland (which became the CARBIFIX company in 2020) and the Oman Drilling Project (OmanDP) under the International Continental Scientific Drilling Program (ICDP). Reservoir characterisation remains a central research focus, as illustrated by projects such as PilotSTRATEGY at the European level and EVASTOCO2 in France. In parallel, the development of monitoring strategies and risk management protocols is currently discussed among the various stakeholders in the storage sector.

Beyond technical considerations, past and ongoing projects—such as the Pycasso pilot in Lacq—have underscored the critical importance of public acceptance for the deployment of CO₂ storage at a given site. Local stakeholders, including public authorities, civil society organisations, economic actors, and institutions, must be adequately informed about the associated risks, benefits, and broader challenges. Research led by Xavier Arnould de Sartre (co-lead of the PEPR “Sub-surface: a common good” and contributor to PEPR SPLEEN) and Sébastien Chailleux (coordinator of the VERTIQUAL project under the PEPR “Subsurface: a common good,” focused on the politicisation of the subsurface) highlights the need to structure a national-level debate on the role and acceptability of CCS, and to facilitate discussions at the local level regarding the various technological options, the comparisons with alternative solutions, and site-specific characteristics. However, the complexity of the CCUS value chain, its integration into the overall decarbonisation strategy, and the uncertainties that still surround certain projects continue to make it difficult for the various stakeholders to effectively communicate about these technologies.

Impurities, monitoring, and life cycle considerations: cross-cutting challenges along the CCUS value chain

The development of CCUS projects has underscored the importance of accounting for the actual quality of captured CO₂, as associated impurities can affect every stage of the process. In particular, impurities introduce specific safety constraints during liquefaction and transport, as they may induce significant corrosion in pipelines and storage infrastructure.

Monitoring is a critical component for ensuring both the safety and credibility of CCUS systems, from capture to geological storage. It encompasses tracking the

migration of injected CO₂ within reservoirs, assessing impurity composition, verifying storage integrity (notably the absence of leakage), managing risks such as induced seismicity, overpressure, and well integrity, and demonstrating long-term climate performance. More broadly, achieving a comprehensive understanding and optimisation of the CCUS value chain requires the implementation of life cycle assessment and performance indicators. These approaches aim to identify critical stages where improvements are most needed. In this context, several organisations, including BRGM, CEA, IFPEN, and CNRS, are developing dedicated tools based on diverse standards and methodological frameworks.

In the context of increasingly stringent climate targets, these analyses underscore the need to validate performance and assess trade-offs between technical and economic dimensions at higher levels of technological maturity. Although CNRS is particularly well positioned in the upstream segments of CO₂ capture and utilisation, it faces challenges in transitioning towards chemical process engineering, a domain largely dominated by IFPEN (notably through its subsidiary Axens) and the CEA. Both academic and industrial stakeholders in the CCUS field therefore emphasise the urgency of advancing the technology readiness level (TRL) across all stages of the value chain through the development of pilot plants and demonstrators. Reaching the level of maturity required for industrial deployment at each stage typically involves around a decade of development.

SCIENTIFIC PUBLICATIONS

Between 2005 and 2023, more than 75,000 scientific publications related to CCUS were produced world-wide. As commonly observed, annual publication output has increased over time (Figure 6), initially driven by interest in enhanced oil recovery applications, and subsequently by the anticipated implementation of environmental policies. A temporary slowdown in scientific activity is nevertheless apparent in the early 2010s, likely reflecting both the absence of a viable economic model and technological barriers that reduced interest in the field. As illustrated in Figure 7, the scientific literature on CCUS is predominantly focused on capture, utilisation, and storage, while transport remains comparatively underexplored. Over time, research on CO₂ utilisation has progressively gained prominence relative to storage.

With more than 2,300 scientific publications on CCUS produced between 2005 and 2023, France ranks 11th worldwide (3.1% of total output) and 4th in Europe, behind the United Kingdom (6.5%), Germany (4.3%), and Spain (3.4%). Although the volume of French publications doubled between 2010 and 2023, its relative share has steadily declined, decreasing from over 5% around 2010 to approximately 2.5% in the early 2020s. Similar trends, albeit to varying extents, are observed in other major contributing countries. This evolution is largely driven by the rapid expansion of research activity in China, which has become the leading contributor in the field, accounting for nearly 50% of global publications in 2023, compared with 23% in 2005. To a lesser extent, other countries such as India and Iran (ranked 12th globally over the period, just behind France) have also increased their presence, effectively doubling their share of global output over the same period.

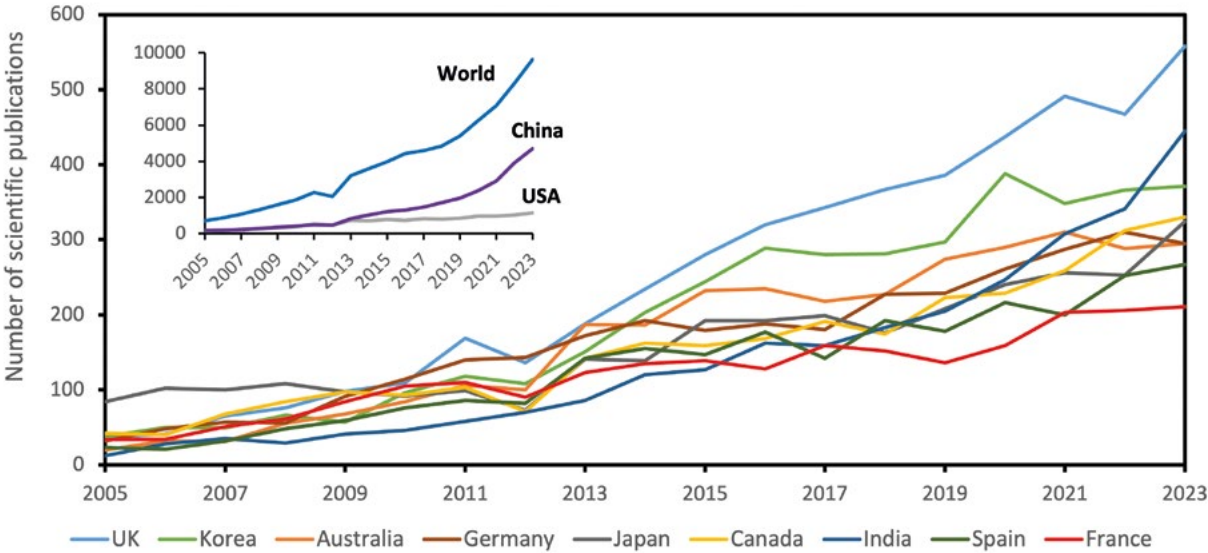


Figure 6: Number of scientific publications by signatory country; the main graph presents the leading countries excluding the United States and China, whose strong growth over the past 25 years is clearly highlighted in the inset

(source: Scopus; VIA INNO)

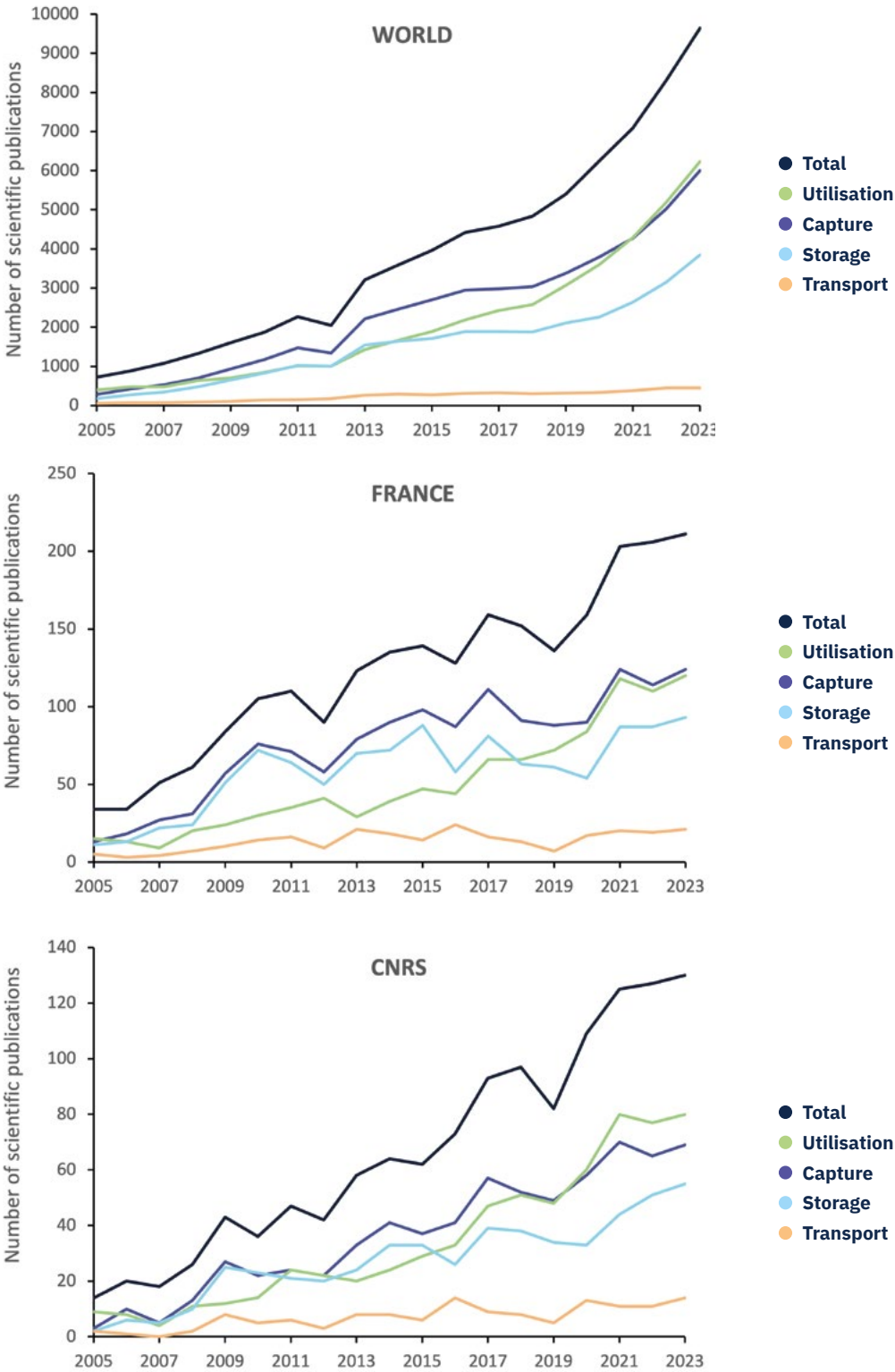


Figure 7: Number of scientific publications by CCUS domain (capture, utilisation, storage, transport, and total) at the global level, in France and within the CNRS

(source: Scopus; VIA INNO)

The CNRS plays a central role in French CCUS research, contributing to nearly 55% of national publications between 2005 and 2023, corresponding to more than 1,250 articles. Its contribution has increased significantly over time, particularly during the 2010s, rising from 40–45% at the beginning of the decade to over 60% from 2018 onwards. Other major French contributors include IFPEN (nearly 180 publications), BRGM, and Mines ParisTech, as well as industrial stakeholders such as TotalEnergies, each with around 100 publications.

As observed at the global level, research on CO₂ capture and storage dominated French scientific output between 2005 and 2015 (Figure 7). Over time, interest in CO₂ utilisation has increased significantly, reaching a level comparable to that of capture in France since the late 2010s. This shift from storage towards utilisation and valorisation of captured CO₂ has been strongly supported by CNRS research, where this theme has emerged as a major focus since the early 2020s.

Figure 8 illustrates the geographical distribution of authors located in France contributing to CNRS publications on CCUS. These publications originate predominantly from laboratories located in the Île-de-France region, followed by those in the Lyon, Toulouse, and Montpellier areas, and to a lesser extent in the Nancy and Grenoble regions.

CNRS publications in this field have achieved a high level of visibility, with more than 60,000 citations recorded in the Web of Science database. This corresponds to an average of approximately 50 citations per publication and an h-index of 117⁴. In addition, around a dozen articles co-authored by CNRS researchers and published in leading interdisciplinary journals such as Nature and Science are classified by Web of Science as “Highly Cited Papers”, meaning they rank among the top 1% most cited publications in their respective field and year (most frequently in chemistry). The ten most cited publications are listed in Appendix 3.

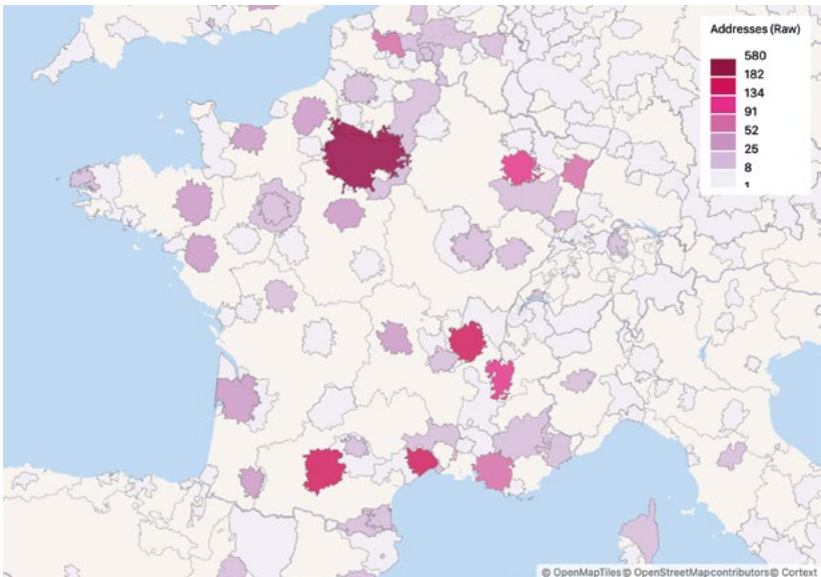


Figure 8: Distribution of the locations of authors of CNRS scientific publications across French metropolitan areas

(source: Scopus/Web of Science; VIA INNO; processed by Cortext Manager)

4. The h-index is a metric of an entity's (researcher, organisation, etc.) publications, equal to the number h of its publications that have each received at least h citations: an h-index of 117 means that 117 CNRS publications on CCUS have each received at least 117 citations, which shows that at least 10% of the papers are widely cited in the scientific literature.

Other CNRS publications, including some issued before 2015, have also attracted substantial citation impact. This is notably the case for a 2012 article co-authored by C. Costentin, S. Drouet, M. Robert and J.-M. Savéant from the Laboratory of Molecular Electrochemistry at Paris Diderot, on the electroreduction of CO₂ to CO using an iron-based catalyst⁵ (1,150 citations). Another highly cited contribution is a 2008 paper involving E. Oelkers (GET, formerly LMTG, Toulouse) on the mineral carbonation of CO₂⁶ (756 citations).

TECHNOLOGY PATENTS

More than 18,000 patent families relating to CCUS were filed worldwide between 2005 and 2021⁷. After a period of strong growth between 2005 and 2011, during which the number of applications doubled, filings slowed and then remained broadly stable for several years before picking up again towards the end of the 2010s and continuing to rise thereafter (Figure 9). The peak observed in the early 2010s was identified as being driven by CO₂ applications for

enhanced oil recovery, echoing the trend seen in scientific publications. This was followed by a more stable phase, and then a renewed increase driven mainly by Asian countries in the late 2010s. Patent applications are concentrated primarily on CO₂ capture and utilisation technologies, which account for about 75% of filings, whereas storage and transport remain relatively underpatented.



The CNRS plays a central role in French CCUS research.

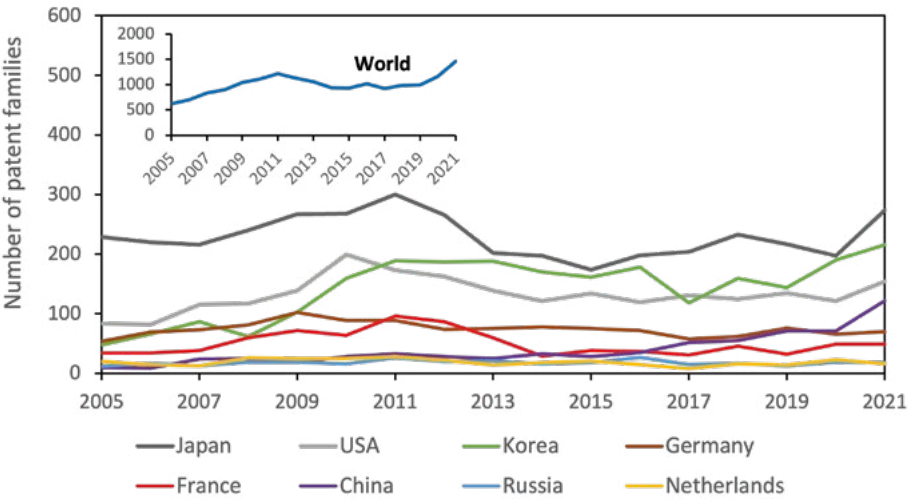


Figure 9: Number of documents related to patent applications

(Questel database, processed by VIA INNO and then CNRS)

5. “A Local Proton Source Enhances CO₂ Electroreduction to CO by a Molecular Fe Catalyst”, Science 338(6103):90-94 (2012)
6. “Mineral Carbonation of CO₂”, Elements 4(5):433-437 (2008)
7. Patent families granted worldwide. Patents granted in China are included only if they have been extended internationally, in accordance with the counting method used in this study.

With around 900 patent applications worldwide, French applicants rank sixth globally over the period considered, accounting for 5% of all applications, behind Germany (7.3%) and well ahead of the Netherlands (1.8%)⁸. The three main French applicants are Air Liquide, which accounts for more than one-third of the patents, followed by Alstom Technology (20%) and IFPEN (15%). TotalEnergies, the CNRS and the CEA come next.

In total, nearly 280 CCUS-related patent applications were filed by the CNRS between 2005 and 2024 with various intellectual property offices worldwide⁹. These applications are distributed across 73 invention families, corresponding to the actual number of distinct inventions in which the CNRS has been involved¹⁰. Most belong to extended families, meaning that the same invention has been filed in several countries or regions, generally through EP or PCT applications and extensions to major offices, often including the United States, and sometimes Japan or China.

These patents mainly concern CO₂ capture technologies, such as absorption, adsorption, membranes and cryogenic processes. A few apply more specifically to CO₂ storage, while more recent filings increasingly focus on CO₂ utilisation, especially reduction pathways for different applications.

CNRS applications are rarely filed by the CNRS alone (14% of families), while the vast majority involve co-applicants. In about one quarter of cases, the co-applicant is a company, usually a large one such as TotalEnergies, Air Liquide, Vicat, Lafarge Holcim, EDF or Syensqo. However, co-applicants are most often French public institutions, including IFPEN, INRAE, BRGM, and universities or higher education institutions.

Looking at the post-filing trajectory of these applications, as recorded in the CNRS Innovation VEGA database, nearly fifty families are still under intellectual property protection today, although only a small number are currently being exploited. Around ten patents have led to technology transfer to SMEs or start-ups, but revenues remain limited so far, at €15,000, compared with total intellectual property costs of €1.15 million, including patent maintenance fees and rights buy-backs, particularly for patents relating to MOFs. This should nevertheless be interpreted with caution, as the current agreements are still relatively recent, most having been signed since 2021, and additional revenue may be generated if future products reach the market.

8. The comparison of patent numbers should be interpreted with caution. It includes applications filed with patent offices worldwide, whose filing rules are not fully harmonized. Some offices, particularly in Asia, are known to apply less stringent selection criteria than offices in Western countries, such as the European Patent Office (EPO).

9. Patent applications in which the CNRS is listed as an applicant in the Espacenet database, the EPO's public database. The CNRS's actual contribution to French inventive activity is likely higher, since these figures include only patents for which the CNRS is an applicant. CNRS researchers also appear as inventors on patents where the CNRS is not the applicant. Recent work by Neuhäusler and Frietsch (2024) shows that the contribution of a higher education institution to inventive activity is, on average, about twice as high when inventor status is taken into account rather than applicant status alone.

10. Patent applications are grouped into extended families (INPADOC families) in Espacenet.

PRE-MATURATION, MATURATION AND START-UPS

CNRS support for innovation and technology transfer is relatively recent. For a long time, the organisation focused primarily on fundamental research with limited immediate commercial application, but it has progressively developed structured mechanisms covering the full innovation value chain. This evolution was marked in particular by the launch of the RISE program in 2019 to support start-up creation, and by the growing role of CNRS Innovation and the SATT network. Unlike the CEA, which has a more integrated model built around its own technology platforms, development units and transfer channels, the CNRS relies on a distributed network of academic laboratories and commercialisation partners across the country, with strong links to local innovation ecosystems. Despite these tools, CNRS scientists involved in CCUS still report major obstacles to technology transfer, especially the lack of pilot sites, for example for storage, and demonstrators.

Since 2020, the CNRS has supported two pre-maturation projects, representing a cumulative investment of around €275,000. In addition, 20 maturation projects originating from CNRS UMRs have been funded by the SATTs since 2013, for a total of **€4.64 million**, to support developments at intermediate TRLs, from 3 to 6. These projects focus mainly on CO₂ utilisation; only three concern capture, and none relate to storage.

Through its knowledge production, patent portfolio and innovation support mechanisms, the CNRS

has also contributed since 2018 to the creation or strengthening of eight start-ups originating from, or affiliated with, CNRS laboratories. Although still recent, several already show strong promise or have reached SME status.



CNRS scientists involved in CCUS still report major obstacles to technology transfer, especially the lack of pilot sites, for example for storage, and demonstrators.

THE MOST NOTABLE EXAMPLES ARE LISTED BELOW, TOGETHER WITH THEIR YEAR OF ESTABLISHMENT AND PARENT LABORATORY:

- **MECAWARE** (2020, ICBMS and ISM2; deployment phase) uses CO₂ to selectively extract critical metals from end-of-life batteries for industrial reuse in the form of carbonates, via an innovative hydrometallurgical process with very high yield and purity. This process, unique worldwide, combines the recovery of captured CO₂ with two major environmental goals: reducing emissions and recycling strategic materials.
- **ENERGO** (2018, IPCM; development phase) has developed a plasma-catalysis technology that converts gases into target molecules more rapidly, more efficiently and with a lower environmental footprint. Applied to CO₂ methanation, this process enables renewable gas production at a cost around 40% lower than conventional approaches. Compact and modular, the system can be located as close as possible to the CO₂ source, in practice biogas derived from agricultural waste, with a view to producing e-fuels for nearby.

- **NETCARBON** (2022, CESBIO; deployment phase) measures and enhances carbon sequestration, particularly in urban and rural environments. The start-up offers an innovative SaaS platform based on satellite data and artificial intelligence to simulate the environmental impact of development or restoration projects using indicators such as urban heat islands, carbon stocks, biodiversity and soil permeability. This enables clients to design more sustainable projects, certify their actions through carbon credits or recognised labels, and communicate results more effectively.

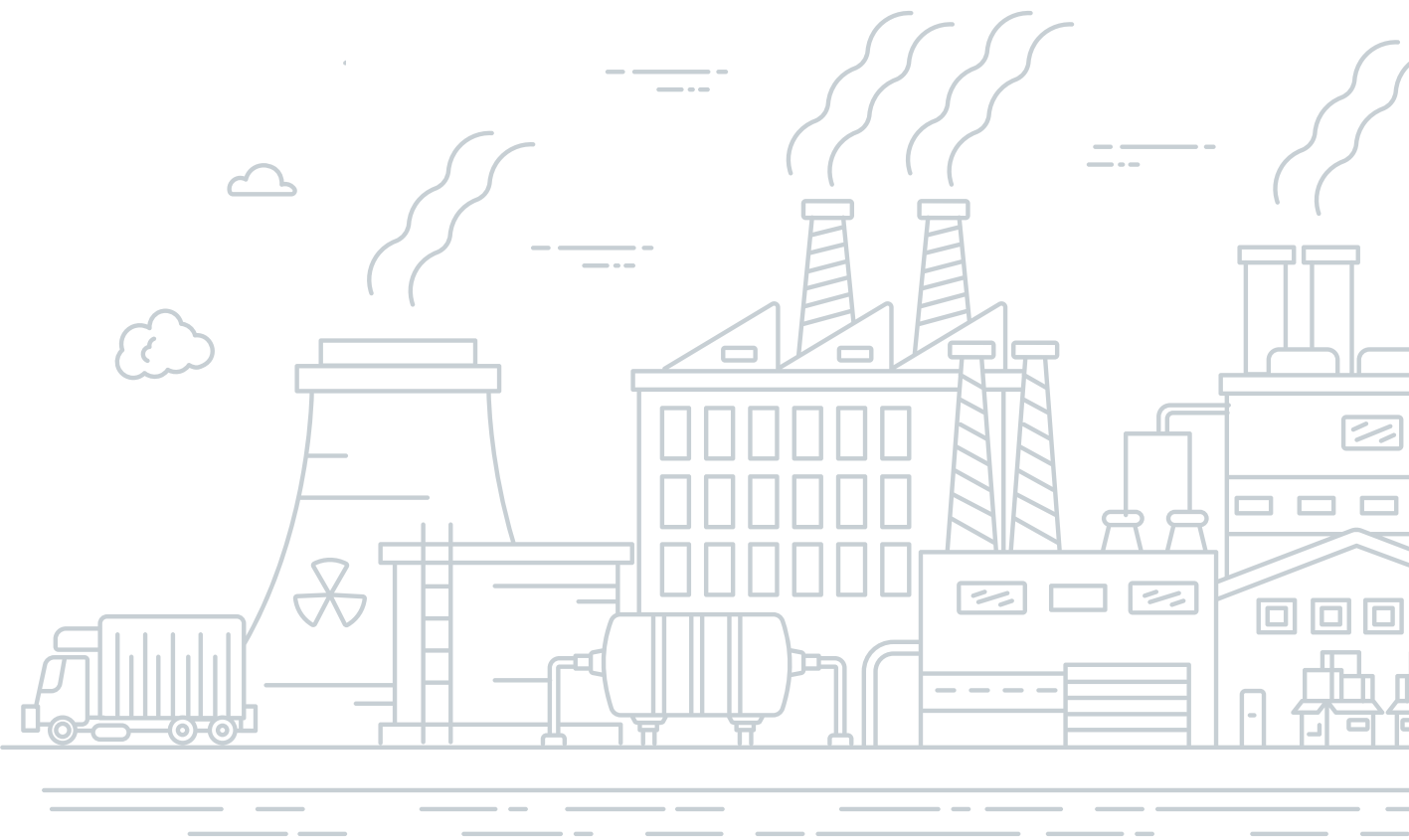
- **DIOXYCLE** (2020, CRPP; development phase) is developing a modular electrolyser powered by renewable electricity that converts CO₂ or CO into ethylene composed entirely of recycled carbon, as a substitute for fossil-based ethylene widely used in the chemical industry.

Other start-ups emerging from CNRS laboratories remain at an earlier stage of development, such as **CARBONEO** (founded in 2020, LEM), which is developing highly durable electrodes for CO₂ electrolysis based on abundant metals such as iron and cobalt.

TRAINING

CNRS laboratories and their partners attract and supervise PhD students from around the world across the various dimensions of CCUS. As a result, nearly 115 doctoral theses on this topic have been defended in France since 2006, across all institutions and not limited to CNRS laboratories (*source: theses.fr*).

Beyond its role in initial academic training, CNRS also provides continuing professional development across a wide range of scientific fields. Although no programme is specifically dedicated to CCUS—unlike those offered by IFPEN and BRGM—two training modules are particularly relevant: “Gas adsorption and applications: characterisation of materials and gas separation or storage” (developed by the MA-DIREL laboratory in Marseille) and “Fundamentals of heterogeneous catalysis” (developed by IC2MP in Poitiers).



KNOWLEDGE sharing and intermediaries

The role of CCUS intermediaries has evolved in parallel with public policy, alternating between periods of caution and renewed momentum. Activity in this area accelerated in 2015 following the Paris Climate Agreement (COP21), engaging major industrial stakeholders, the French government, and European institutions.

Following this agreement, most large companies adopted decarbonisation roadmaps targeting carbon neutrality by 2050. A second major acceleration occurred with the adoption of the Inflation Reduction Act (IRA) in 2022 under Joe Biden presidency, which introduced a range of measures supporting the energy transition, including a formalised framework for carbon credits in the United States. This initiative stimulated the development of industrial hubs dedicated to hydrogen and CO₂ storage, creating a new international dynamic involving public authorities, industry, start-ups, and academia. More recently, as noted by Régis Réau (Air Liquide), major chemical

companies remain cautious, awaiting both greater policy stability in the United States and the consolidation of viable economic models. In this context, the European Commission adopted in March 2026 a legislative proposal—the Industrial Accelerator Act (IAA)—aimed at strengthening demand for low-carbon technologies and products manufactured in Europe. These successive developments have progressively contributed to the structuring of CCUS intermediaries, albeit at varying speeds depending on the sector and geographical context.

NATIONAL AND EUROPEAN POLITICAL INSTITUTIONS

In response to the 2015 Paris Agreement, the European Green Deal sets the objective of achieving climate neutrality in Europe by 2050. It also targets a reduction in CO₂ emissions of at least 50% by 2030 compared with 1990 levels—aiming for 55% if possible—while making the 2050 neutrality goal legally binding through the European Climate Law, with an emphasis on economic viability and social fairness. To support these ambitions, the European Union has established a comprehensive set of regulatory and financial instruments. A central pillar is the “Fit for 55” legislative package, which includes, among other measures, revisions to the Effort Sharing Regulation (EU Directive 2023/857) and the EU Emissions Trading System (EU ETS; Directive 2003/87/EC, as amended by Directive 2023/959). The EU ETS operates as a cap-and-trade system for greenhouse gas emissions within the European Union, based on a progressively declining cap on total allowances. It covers the energy sector, several energy-intensive industries (including steel and construction), as well as aviation and maritime transport, collectively accounting for around 40% of total EU emissions. Since its launch in 2005, the system has contributed to a 46% reduction in emissions within its scope (*source: Energy Regulatory Commission*).

In February 2024, the European Commission published an industrial carbon management strategy for 2030 and 2050, reaffirming the importance of deploying carbon capture, utilisation, and storage (CCUS) to achieve climate neutrality. This strategic direction was translated into legislation in June 2024 through the Net-Zero Industry Act (NZIA), which sets a target of capturing and storing 50 MtCO₂/year within Europe. In parallel, the Commission has strengthened the regulatory framework for sustainable energy sources, particularly e-fuels in aviation and maritime transport.

From 2030, the revised Renewable Energy Directive (RED II) requires the incorporation of at least 1% of renewable fuels of non-biological origin (RFNBOs) in transport. The ReFuelEU Aviation and FuelEU Maritime initiatives establish progressive targets up to 2050, with specific blending quotas: in aviation, 20% sustainable fuels by 2035—including 5% bio-based e-fuels—rising to 70% by 2050, including 35% e-fuels; in maritime transport, a minimum of 2% e-fuels from 2034. In addition, Europe supports the CCUS sector through the framework programme for R&D-related activities. Finally Europe mobilises the Innovation Fund, financed by the sale of CO₂ allowances from the EU ETS, to support innovative industrial projects with high environmental value and promote the deployment of low-carbon technologies, in particular disruptive innovations contributing to the decarbonisation of the highest-emitting sectors. French companies have thus benefited from €527 million from this fund since 2021.

The French implementation of the Green Deal, the National Low-Carbon Strategy (SNBC), sets out a roadmap based on energy efficiency and conservation, the development of renewable energy sources, and the electrification of end uses (Figure 10). Within this framework, a specific trajectory is defined for each sector of the economy, particularly industry (Figure 11). Although France has long favoured decarbonisation through low-carbon electricity and energy efficiency (notably thanks to its nuclear fleet) rather than CCS and CCU, the need to deploy these solutions is now clearly established in order to reduce industrial CO₂ emissions (currently 63 Mt) by 68% by 2030 compared with 1990 levels (45 Mt compared to 140 Mt), and then by 97% by 2050 (4 Mt).

The deployment framework, intended to provide stakeholders with regulatory and financial visibility, is structured as follows (DGE, 2024):

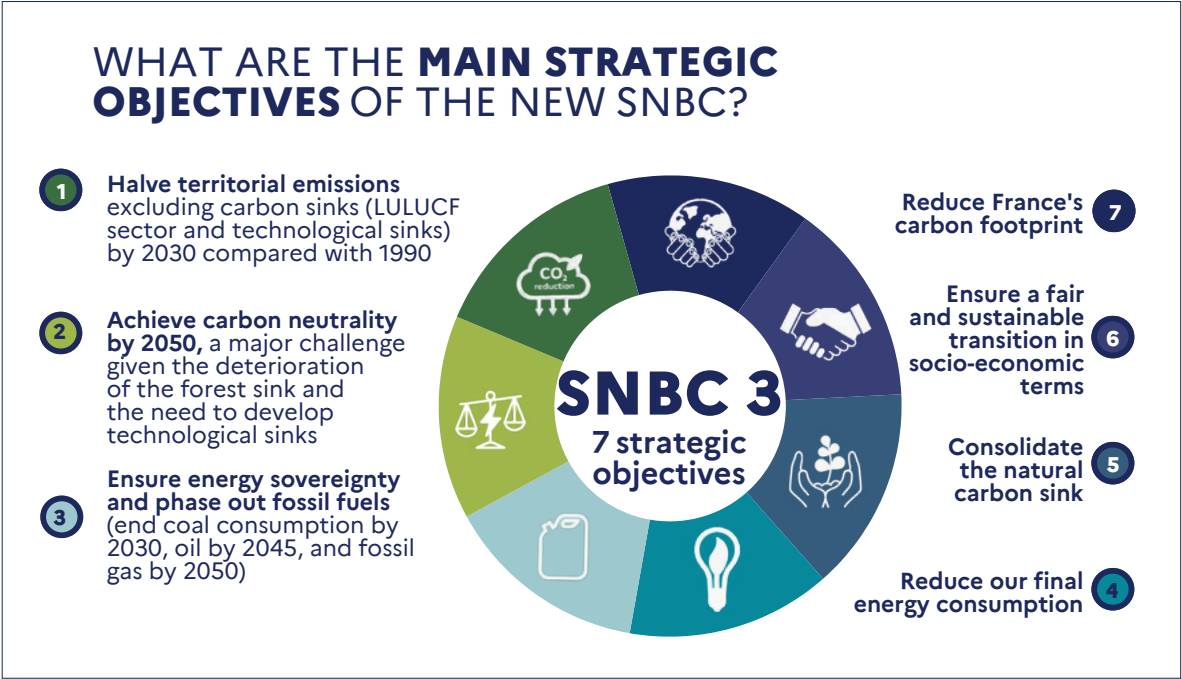
- 1

PHASE 1 (2024-2030):
the development of at least two CCUS hubs would make it possible to achieve capture volumes of 4 to 8 MtCO₂/year by 2030.
- 2

PHASE 2 (2030-2040):
the development of sovereign storage facilities and regulatory changes would enable capture of 12 to 20 MtCO₂/year by 2040.
- 3

PHASE 3 (2040-2050):
captured CO₂ volumes could reach 30 to 50 MtCO₂/year.

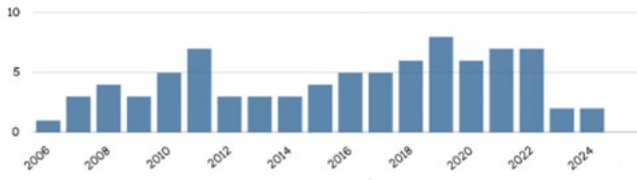
It should also be noted that the CO₂ requirement for producing e-SAF is estimated at around 15 MtCO₂/year in order to meet the ReFuelEU Aviation and FuelEU Maritime regulations.



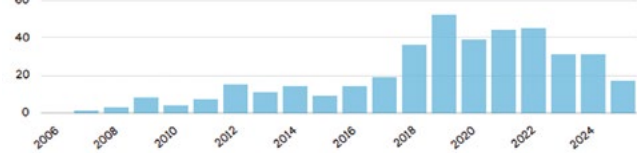
The most frequently cited authors include Éric H. Oelkers (CO₂ storage) and Philippe Ciais (carbon cycle). The majority of these policy documents are produced by the United Nations and its agencies, the European Union (Publications Office), as well as international organisations such as the World Bank and the OECD. They mainly address the Sustainable Development Goal 13 on climate action. Some documents also originate from national institutions, particularly in Spain, the United States, Germany, and Switzerland, and focus on issues such as decarbonisation, CO₂ storage, and negative emissions. These policy documents are, in turn, cited in 24,084 additional policy documents produced by 1,209 sources across 117 countries, highlighting the broad dissemination of scientific and evidence-based information within policy networks. In France, however, influence appears to rely less on the direct citation of scientific publications than on the reuse of these intermediary policy documents, with 912 such documents identified. These are cited primarily by think tanks and NGOs based in France, and to a lesser extent by public institutions—including government departments, ADEME, the High Council for Climate, ANSES, and OPECST—often within documents addressing issues that extend well beyond CCUS.

In summary, more than a decade was required to stabilise a political position on CCUS in France and Europe. These years of stop-and-go (‘We’ve moved from a “maybe” approach to CCUS to a “must” imperative to achieve carbon neutrality by 2050’, Hoang Bui, SGPI) have significantly delayed the implementation of industrial roadmaps and the deployment of innovations—whether disruptive or even incremental—, especially as political debates have seldom been grounded in scientific evidence. This sustained political hesitations now jeopardises the achievement of the national strategy’s quantified targets within the prescribed timeframe.

Years of publication of scientific articles



Years of publication of policy documents



Years of publication of policy documents that themselves cite other policy documents

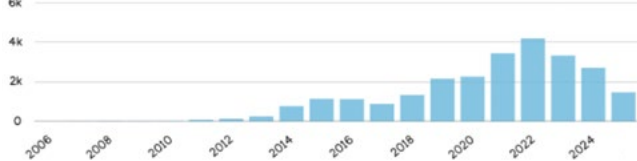


Figure 12: References to scientific publications in policy documents. The top panel presents the publication years of CNRS scientific outputs on CCUS cited in policy documents. The middle panel shows the annual number of policy documents citing these publications. The bottom panel illustrates the yearly number of policy documents that, in turn, cite these policy documents. (source: Overton)

PUBLIC AND PRIVATE INVESTORS

In France, in addition to public-sector actors, approximately one hundred investment funds hold the Greenfin label (formerly TEEC, established by AFNOR). This label certifies that financial products contribute effectively to the energy and ecological transition. These actors rely on the European Green Taxonomy, a regulatory framework designed to assess and transparently report the “green” component of economic activities or financial products based on six criteria:

- **mitigation** of climate change;
- **adaptation** of climate change;
- **sustainable use and protection** of water and marine resources;
- **transition** to a circular economy;
- **pollution prevention** and control;
- **and protection and restoration** of biodiversity and ecosystems.

This framework enables the quantification of environmental impact through defined indicators and monitoring mechanisms, provided that companies supply reliable data, conduct carbon footprint assessments, and perform long-term life-cycle analyses—including projections for low-TRL technologies. However, no dedicated CCUS-specific label currently exists, nor are there investment funds exclusively focused on CCUS.

Investors play a critical role in advancing projects along the Technology Readiness Level (TRL) spectrum, providing funding from early-stage laboratory research through to market entry, including initial public offerings (IPOs). However, CCUS projects raise significant concerns related to technological maturity, the uncertainty of short- and medium-term financial returns, their actual environmental performance, and the public perception. In addition, no single investor covers the entire CCUS value chain. The landscape is highly fragmented, with numerous interdependent actors fulfilling distinct roles. At the same time, the overall business model remains unstable and exposed to risk, notably due to CO₂ price volatility and delays in political and regulatory frameworks.



More than a decade was required to stabilise a political position on CCUS in France and Europe. These years of stop-and-go have significantly delayed the implementation of industrial roadmaps and the deployment of innovations.

TO MEET CO₂ EMISSION REDUCTION TARGETS AND ADDRESS THESE CHALLENGES, THE GOVERNMENT HAS IMPLEMENTED A RANGE OF FUNDING AND SUPPORT MECHANISMS TARGETING STAKEHOLDERS AT DIFFERENT STAGES OF DEVELOPMENT. THE MAIN INSTRUMENTS INCLUDE:

- **THE PEPR PROGRAM**, which supports upstream research activities (TRL 1–4).
- **THE DEMIBAC CALL FOR PROJECTS**, focused on the development of technological building blocks and demonstrators, supporting industrial innovation from research phases through to demonstration, with the objective of accelerating the market deployment of decarbonisation solutions.
- **THE IBAC CALL FOR PROJECTS DEDICATED TO SMES**, aimed at developing technological building blocks and services for industrial decarbonisation.
- **THE “GRANDS PROJETS INDUSTRIELS DE DÉCARBONATION” (GPID) CALL FOR TENDERS**, targeting industrial sites covered by the EU Emissions Trading System (ETS). The first selection wave, announced in February 2026, includes three CO₂ capture projects in cement industries and one in the aluminium sector.

- **THE “ZONES INDUSTRIELLES BAS CARBONE” (ZIBAC) SCHEME**, which supports the development of shared decarbonisation infrastructure—including CCUS—by funding collaborative studies in major industrial areas. The ten selected zones together account for approximately 70% of France’s industrial CO₂ emissions.
- **THE DEPLOYMENT OF CARBON CONTRACTS FOR DIFFERENCE (CCfD)** at the European level was designed to mitigate carbon price uncertainty for companies engaged in decarbonisation. These mechanisms compensate for the gap between the market price of CO₂ and a reference price reflecting the cost of avoided or captured emissions (e.g. CCS). An alternative approach currently under consideration in France involves setting a predefined trajectory for CO₂ prices over the coming years, thereby reducing the need for extensive public financial commitments to hedge against price volatility.



It should be noted that, to date, the French government has chosen not to take a direct role in the development of shared infrastructure, such as CO₂ transport pipelines, which could otherwise be managed as common assets.

The government also intervenes through the Public Investment Bank (Bpifrance), which supports companies via loans, guarantees, innovation grants, and equity investments. As an operator of the France 2030 programme, Bpifrance acts in alignment with national public policies. In this context, the i-Lab programme (supporting the creation of innovative start-ups) and the i-Demo programme (supporting, in particular, industrial and pre-industrial demonstrators) already include several successful CCUS-related projects. As a member of the Corporate Venture Capital Club of France Invest—a professional association representing private equity, debt, and infrastructure stakeholders—Bpifrance also contributes to mobilising industrial partners and private banks in risk-sharing mechanisms. Nevertheless, projects at intermediate maturity levels (TRL 5–8) remain insufficiently supported by public funding.

Investor caution regarding CCUS within the broader energy and ecological transition is partly driven by concerns that the sector may embody a form of techno-solutionism. For example, e-SAF (electro-sustainable aviation fuels) can be perceived as shifting, rather than eliminating, CO₂ emissions associated with air transport. Similarly, onshore CO₂ storage raises not only technical concerns—such as leakage and induced seismicity risks—but also socio-economic issues, including potential job losses compared with traditional resource exploitation, as illustrated by the Lacq site. These reservations mirror concerns expressed by civil society. By contrast, direct air capture (DAC) may be viewed by some investors as a more

virtuous and promising option—owing to its perceived higher efficiency and reduced reliance on rare materials—despite its significant energy requirements.

More broadly, French investors tend to adopt a more risk-averse approach than their American counterparts do. Commercial viability is a decisive criterion, alongside team quality and the robustness of the business model. As a result, disruptive technologies often struggle to attract funding, particularly since most private investors rely only marginally on scientific expertise in their decision-making processes. Instead, they tend to favour demonstrators and high-TRL projects, which are perceived as less risky.

CO₂-EMITTING INDUSTRIAL SECTORS

In 2024, French industry (manufacturing, construction, and metallurgy) remains the third-largest source of greenhouse gas emissions, behind transport and agriculture, with 62.4 MtCO₂, representing 16.9% of national emissions. The main emitting sectors are steelmaking, aluminium production, chemicals, and cement. Owing to France’s largely decarbonised electricity mix, the energy sector accounts for a comparatively limited share (12%). Although industrial emissions have declined significantly since the 1990s (approximately –60%), this reduction is often linked to decreased production levels rather than to structural transformations in industrial processes. Progress in decarbonisation therefore remains uneven across sectors, although some manufacturers—notably in the cement industry—are beginning to implement substantial measures.

Emissions are geographically concentrated in major industrial hubs, particularly around Dunkerque, Fos-sur-Mer, the Rouen—Le Havre axis, and the Grand-Est region. ArcelorMittal is the largest emitter, ■■■

■■■ accounting for approximately 20% of industrial CO₂ emissions in France, with major sites in Dunkerque and Fos-sur-Mer. It is followed by key actors in the chemical sector (including Naphtachimie and LyondellBasell in Bouches-du-Rhône, and TotalEnergies in Gonfreville, Seine-Maritime) and cement producers (Lafarge Holcim in Mayenne, Ciments Calcia in Marne, LAT Nitrogen in Seine-et-Marne, and Vicat in Montalieu, Isère). For these industries, carbon capture and storage (CCS) is generally considered as a solution of last resort, used when alternative decarbonisation options—such as electrification, energy efficiency, demand reduction, or process innovation—are insufficient to eliminate so-called “hard-to-abate” emissions. Some stakeholders are also exploring carbon capture and utilisation (CCU), with potential applications in biofuels, chemicals, advanced materials, and the agri-food sector. However, beyond the financial and energy requirements, certain pathways—such as e-fuel production—will require certification of the biogenic origin of CO₂, progressively replacing fossil-derived sources of CO₂.

At present, most industrial actors remain at the stage of planning pilot CCS installations and awaiting final investment decisions, which are not expected before 2027–2028 for the most advanced projects. Nevertheless, recent policy developments and funding decisions—particularly through the European Innovation Fund and the French GPID programme—indicate that CCS deployment is likely to accelerate in the medium term.

Cement sector

In France, 20 cement plants are among the 50 largest industrial CO₂ emitters. Carbon capture and storage (CCS) is considered essential to address the estimated 23% of emissions that cannot be avoided through conventional measures, and to help achieve a 50% reduction in sectoral emissions by 2030. The cement industry is particularly well suited to carbon capture due to the high concentration of CO₂ in flue gases at the preheater outlet (approximately 30%), which facilitates capture processes. **The sector decarbonisation roadmap relies on two main categories of levers:**

- 1

CONVENTIONAL MEASURES,
including energy decarbonisation, improvements in site energy efficiency, substitution of fossil fuels (e.g. petroleum coke) with non-recyclable waste (e.g. tyres, waste oils), and reduction of clinker content or its partial replacement with lower-carbon materials.
- 2

CCS AND, IN SOME CASES CCU.
CO₂ captured from cement plant flue gases originates from two main sources: process emissions resulting from the calcination of limestone, which are unavoidable, and combustion emissions from fuels, including non-recyclable waste that may contain a proportion of biomass. As a result, an estimated 15–20% of the captured CO₂ is of biogenic origin and may be valorised, notably in the production of e-fuels.

Vicat, the last fully French-owned cement manufacturer, provides a representative example of an industrial player investing across the complete spec-

trum of decarbonisation levers. Its main French plant in Montalieu (Isère) has virtually eliminated the use of fossil fuels, replacing them with various energy-from-waste sources. Combustion residues are reintegrated into clinker production. In parallel, clinker reformulation—particularly through the incorporation of activated clays—has enabled the development of lower-carbon products, commercialised since 2009 (initially in Brazil, and more recently in France and the United States). These approaches, addressing both energy inputs and product composition, are now mature and supported by established markets. To address unavoidable process emissions, Vicat is leading the VAIA (Vicat Advanced Industrial Alliance) project as part of the Rhône Décarbonation initiative. The objective is to capture up to 100% of residual CO₂ emissions at the Montalieu site and transport them for storage in depleted gas fields in Ravenna (Adriatic Sea). The planned logistics chain involves transport via an existing pipeline to Fos-sur-Mer (operated by SPSE), followed by liquefaction and interim storage (by Elengy), and subsequent shipment to the ENI-operated storage site. The capture system is expected to combine amine-based absorption with a cryogenic process, such as those developed by Air Liquide. Vicat is also exploring carbon utilisation pathways. The company has acquired a stake in Genvia, which is developing high-temperature electrolysis technology (originating from CEA) to produce hydrogen using waste heat from cement plants, with the aim of converting captured CO₂ into e-fuels.

Aluminium sector

Aluminium production is among the most CO₂-intensive industrial processes, and carbon capture in this sector remains technically challenging due to the very low concentration of CO₂ in flue gases (typically below 1%). A key challenge lies in devel-

oping efficient pre-concentration systems upstream of capture, potentially involving amine-based processes adapted to the specific characteristics of emissions from electrolysis cells.

As a leading producer of low-carbon aluminium, Aluminium Dunkerque has initially focused on improving process energy efficiency and expanding recycling capacities (2022–2026). The company is now entering a new phase (2026–2030) involving the development of CO₂ capture solutions. In the longer term, it aims to deploy inert anode technology by 2035, which would eliminate direct CO₂ emissions from the electrochemical reduction of alumina. In this context, Aluminium Dunkerque is collaborating with Fives, Trimet, and Rio Tinto on the C4 Capture project to develop sector-specific CO₂ capture solutions. Following validation and prototyping phases, pilot tests under industrial conditions began in January 2026 at the Dunkerque and Saint-Jean-de-Maurienne sites.

Steel industry

The steel industry remains particularly challenging to decarbonise due to the diversity of gaseous emissions generated at different stages of production. These include coke oven gas (H₂, CO, CH₄), blast furnace gas (CO, CO₂, N₂, H₂), and basic oxygen furnace gas (CO, CO₂). This variability in gas composition complicates both regulatory compliance and the implementation of standardised CO₂ capture solutions. The economic viability of carbon capture installations—given their high capital costs—depends on long-term, stable operating conditions. Structural changes in production processes, such as large-scale electrification, could significantly alter or reduce these emission streams, thereby affecting the relevance of capture infrastructure. In this context, ArcelorMittal revised its decarbonisation strategy for its Dunkerque site ■■■

■■■ in early 2026, announcing a €1.3 billion investment in an electric arc furnace, half of which will be financed by the group. In parallel, an industrial pilot project for CO₂ capture from blast furnace gas was conducted between April 2023 and 2024 at the same site. This project aimed to validate the DMX™ process, an advanced amine-based solvent technology developed by IFPEN within the framework of the European H2020 “3D” project and the ADEME-supported DinamX programme. The pilot successfully met its objectives, and the DMX process is now commercially available through Axens, a subsidiary of IFPEN.

Chemical sector

In contrast, the chemical industry has so far committed relatively limited investment to deep decarbonisation based on structural process transformations. One notable initiative is the Eco2Normandy project, led in particular by LAT Nitrogen in Grand-Quevilly and Yara in Le Havre, which aims to implement CO₂ capture and storage solutions by 2030.



CCUS development does not rely on a fully integrated industrial sector, but rather on a still-evolving ecosystem shaped by the interaction of diverse technologies, infrastructures, and major industrial actors pursuing differing strategies.

INDUSTRIAL PLAYERS IN THE CCS AND CCU SECTORS

This section examines the key industrial segments of the CCS and CCU value chains, from CO₂ capture to transport, utilisation and storage, and identifies the main stakeholders involved at each stage. It also highlights that CCUS development does not rely on a fully integrated industrial sector, but rather on a still-evolving ecosystem shaped by the interaction of diverse technologies, infrastructures, and major industrial actors pursuing differing strategies.

CO₂ capture

In most cases, CO₂ capture is implemented directly at the emission source, where it must be separated from flue gases generated by industrial combustion or biomass processing. By contrast, direct air capture (DAC) extracting CO₂ from ambient air presents distinct technical challenges (see the “Technology Innovators” section on page 58). Both situations differ primarily in terms of CO₂ concentration (which is ‘only’ 400 ppm in the air) and also the purity of the CO₂ they aim to produce. Nitrogen, oxygen, and water vapour are the gases most commonly found alongside CO₂, which generally makes up around 15% of the mixture.

In France, several industrial players are already active in flue gas CO₂ capture. Air Liquide develops cryogenic separation technologies; IFPEN, through its subsidiary Axens, specialises in amine-based processes; and Technip Energies deploys solutions based on Shell’s CANSOLV® system. At the same time, emerging companies such as Revcoo and Cryopur are developing more targeted CO₂ purification approaches.

At industrial scale, CO₂ capture from flue gases is most commonly achieved through chemical absorption

using solvent systems, typically based on alkanolamines. These solvents selectively react with CO₂ to form carbamates or carbonates. Once saturated, the solvent is regenerated by heating, releasing high-purity CO₂ (generally exceeding 98%) and enabling solvent recycling within the process. This technology is currently the most mature and widely deployed. However, despite its technical robustness, amine-based capture faces several limitations, including high energy requirements for solvent regeneration and the handling of large volumes of potentially toxic and corrosive compounds (including degradation products such as nitrosamines). To address these challenges, alternative solvents are being developed, including so-called demixing amines, which exhibit liquid—liquid phase separation at moderate temperatures. This approach, developed by IFPEN and commercialised by Axens, enables more energy-efficient CO₂ capture (see the “Technology Innovators” section).

OTHER SOURCE-BASED CO₂ CAPTURE TECHNOLOGIES, AT VARYING LEVELS OF MATURITY, ARE WORTH MENTIONING:

- **ADSORPTION ON POROUS SOLIDS**, particularly MOFs.
- **CRYOGENIC CAPTURE**, in which flue gases are cooled in a cryogenic unit to partially condense CO₂. The purified CO₂ stream is then compressed to a supercritical or liquid state for storage. This approach, developed by companies such as Air Liquide and start-ups including Cryopur (a spin-off from Mines ParisTech, now part of La Française de l’Énergie) and Revcoo, is beginning to be deployed—for example at Air Liquide’s Port-Jérôme site and in

projects led by Eqiom, Lhoist, and Vicat. However, it remains highly sensitive to inlet gas purity, requiring the prior removal of water, sulphur oxides, and nitrogen oxides.

- **SELECTIVE MEMBRANE SEPARATION**, which offers advantages in terms of operational simplicity and scalability. Its performance depends on achieving an optimal balance between permeability and selectivity. However, it requires energy-intensive gas compression (or vacuum conditions) and is sensitive to contaminants.
- **CALCIUM LOOPING CAPTURE**, based on the reversible reaction between quicklime (CaO) and CO₂ to form calcium carbonate (CaCO₃). The latter is subsequently calcined to release CO₂ and regenerate CaO.



CO₂ transport

CO₂ transport is a critical component of CCUS strategies, enabling the transfer of captured CO₂ to utilisation sites or to medium- and long-term storage locations.

More upstream approaches are also being explored, particularly electrochemical capture methods, which could significantly reduce process emissions if powered by low-carbon electricity. Current systems often rely on redox-active organic molecules (e.g. viologens), which remain sensitive to oxygen and moisture, and therefore require further development.

At a scientific research level, many CNRS laboratories are actively involved in early-stage (low TRL) investigations across these technologies (see Appendix 2). In particular, MOF-based materials—of which more than 100,000 structures have been reported—are a major focus of research. High-throughput screening platforms have been developed, notably at IMAP. Among recent advances, the Calgary Framework (CALF)-20, discovered by George Shimizu (University of Calgary), shows promising possibilities as it traps CO₂ more effectively than water. Produced at scale in Europe by BASF, this material underpins patented technologies exploited by the company Svante (which acquired Carbon Alpha in March 2026) for post-combustion capture. Supported by significant public investment in Canada since 2022, these technologies are now progressing toward industrial deployment. In Europe, pilot and demonstration projects have already been conducted (e.g. in Dunkerque) or are currently underway (e.g. in Brindisi), involving IFPEN and industrial partners.

Pipeline transport is a well-established solution, widely used globally in other industrial contexts. Whether onshore or offshore, CO₂ is typically transported in a dense (supercritical) phase, and several thousand kilometres of pipelines are already in operation worldwide—primarily in the United States for enhanced oil recovery. Since the 1980s, this infrastructure has supported the transport of approximately 50 MtCO₂/year. However, scaling up pipeline networks for CCUS presents significant challenges. The primary constraint lies in the high capital cost of infrastructure required to handle large volumes (estimated at 4–5 MtCO₂/year by 2032 for the Dunkerque area alone), compounded by routing constraints in densely populated regions. Technical risks must also be managed, particularly the potential for pipeline rupture due to the specific thermophysical properties of supercritical CO₂. In addition, corrosion is a major concern and depends strongly on gas purity: the presence of oxygen, nitrogen, and sulphur compounds can lead to the formation of acidic species (notably nitric and sulphuric acids in the presence of water), which are highly corrosive to steel. This issue remains insufficiently studied and represents a potential area of contribution for specialised research groups, including CNRS laboratories (e.g. IJL Nancy, IRCP Paris, CIRIMAT Toulouse).

Maritime transport offers a potentially more flexible and cost-effective alternative for long-distance transport or offshore storage. In this case, CO₂ is transported in liquid form under low-temperature and moderate-pressure conditions. Its higher density compared with methane allows for smaller storage volumes, enabling the use of vessels with capacities in the range of

10,000 to 30,000 m³, compared with 120,000 to 150,000 m³ for LNG carriers. While transport by road or rail is technically feasible, these options are generally limited to small-scale or short-distance applications.

At present, relatively few CNRS laboratories are engaged in research on CO₂ transport. Nevertheless, the sector is beginning to structure itself around key industrial actors involved in transport, liquefaction, and export infrastructure within emerging industrial hubs. These include NaTran, SPSE, and Air Liquide for pipeline transport, as well as Elengy and Dunkerque LNG for liquefaction, interim storage, and export. More broadly, around 15 companies expressed interest in developing CO₂ transport infrastructure—such as repurposed pipelines, export hubs, and dedicated logistics—in response to a 2024 call for expressions of interest aimed at structuring the CCS value chain in France from 2025 onwards..

CO₂ utilisation

The utilisation of CO₂ faces both thermodynamic and kinetic constraints. In CO₂, carbon is in its highest oxidation state, making its reduction energetically demanding, while its chemical inertness results in high activation barriers in the absence of efficient catalytic systems. Consequently, CO₂ is a thermodynamically stable and weakly reactive molecule, and its conversion requires substantial energy input, suitable catalysts, and/or specific reaction conditions. The resulting products are therefore costly to produce and typically require significant quantities of energy and hydrogen (and thus water), although part of this energy can be recovered during use, particularly in the case of e-fuels.

Current uses of CO₂ remain limited in both scope and volume. It is directly employed in several sectors, including the agri-food industry (preservation, cooling, flavour and caffeine extraction, carbonation of beverages; approximately 600 kt/year in France), urea production (around 300 kt/year), metallurgy (shielding gases for welding and cryogenic applications), and horticulture (greenhouse enrichment), as well as other niche uses (around 200 kt/year). Altogether, this represents a market of roughly 1.1 MtCO₂/year in France, which is not expected to expand significantly in the short term. Approximately 40% of this CO₂ originates from bioethanol or biogas production, 20% from refineries, and 17% from ammonia production. It is most often transported in liquid form by road (see above).



The most promising applications of CO₂ are those still under development at industrial scale, aiming to close the carbon cycle by replacing fossil feedstocks with CO₂-derived products. In such systems, CO₂ is converted into fuels or chemicals that, after use, release CO₂ again, forming a circular pathway. For these approaches to be sustainable, they must rely on low-carbon electricity, green hydrogen, and, increasingly, CO₂ from biogenic or atmospheric sources rather than fossil origins, which are expected to be phased out by 2041.

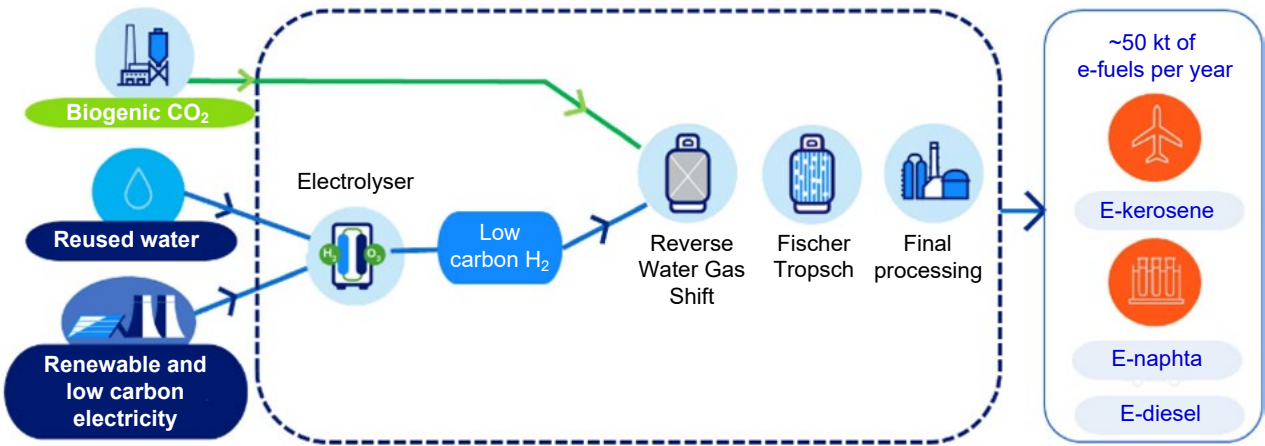
The main industrial applications for CO₂ utilisation currently fall into three main sectors:

• **Synthetic fuels (e-fuels)**, particularly Sustainable Aviation Fuels (SAF) and marine fuels (e.g. e-diesel and e-methanol). These can be produced via biological pathways (such as microalgae-based conversion) or thermochemical routes, notably Fischer—Tropsch synthesis. One illustrative example is the Take Kair project, which aims to build and operate an e-fuel production plant in Donges (Saint-Nazaire port area)

by 2030. The project plans to produce hydrogen via water electrolysis, which will then be used to reduce CO₂ captured from cement plants and convert it into synthetic fuels through Fischer—Tropsch processes. With an estimated investment of €800—900 million, the project is led by Hynamics (EDF subsidiary) and RTE, in partnership with IFPEN, Axens, Air France—KLM, and Holcim (Figure 13). It is currently undergoing public consultation.

CO₂ electroreduction represents another promising route for producing e-fuels, either directly (e.g. alcohols or hydrocarbons) or indirectly via intermediates such as carbon monoxide or methanol. While research activity in this field is intense, challenges related to reaction selectivity, energy efficiency, and catalyst stability at scale mean that these technologies remain at low TRLs. To date, only a limited number of start-ups, often originating from academic research, are pursuing this approach.

Figure 13: The Take Kair project (source: IFPEN)



• **Basic chemicals**, as several simple molecules can be synthesised through CO₂ reduction (so-called e-chemicals). These include methane, methanol (for which several pilot and semi-industrial plants already exist), ethanol, formic acid, some olefins (ethylene and propylene), polymers, and synthesis gas. These processes generally require high-purity CO₂. The potential global market is substantial, and many industrial players in the chemical and energy sectors are actively exploring these pathways, including Syensqo, Arkema, TotalEnergies, INEOS, BASF, and IFPEN. For example, the Hynovi project, led by Vicat and Hynamics, aims to produce low-carbon methanol from CO₂ captured at the Montalieu cement plant. Similarly, the eM-Rhône project, led by Elyse and supported by the European Innovation Fund, plans to produce e-methanol using CO₂ captured from the Lafarge Holcim plant in Ardèche.

• **Construction materials**, which involve the incorporation and permanent fixation of CO₂ in mineral matrices through carbonation reactions. These relatively mature technologies (TRL 7—9), though still energy-intensive, are already being deployed at industrial scale in some cases. They include the stabilisation or solidification of mineral waste into aggregates for concrete (including recycled aggregates), as well as the direct carbonation of concrete, which can enhance mechanical strength and reduce curing time. These pathways enable long-term CO₂ storage (exceeding 100 years) and can, in some cases, utilise flue gases directly without requiring high-purity CO₂.

The market potential is considerable, and major cement producers (Vicat, Lafarge Holcim, Heidelberg Materials) are actively developing these solutions.

According to CO₂ Value Europe, about 180 Mt of precast concrete could incorporate CO₂ by 2050.

In addition to these chemical pathways, various biological approaches—which are not discussed here—are also under development for CO₂ conversion.

CO₂ storage

In contrast to CO₂ capture and utilisation, geological storage relies on a relatively limited number of industrial actors with specialised expertise in subsurface geology, drilling, reservoir management, and the ability to manage long-term projects—a characteristic specific to geological storage. In France, TotalEnergies plays a central role, both through industrial partnerships and via a number of joint research chairs established with CNRS laboratories or IFPEN. Alongside this major player, more specialised companies in the fields of subsurface resources, infrastructures or engineering—such as Geostock, Teréga, Vermilion, and Arverne—are increasingly involved in studies and pilot projects. The development of CO₂ storage therefore depends on the structuring role of large operators capable of managing long-term liabilities and coordinating stakeholders, including industry, public authorities, and local communities.

The main challenges are not solely technical, as many of the required competencies—particularly in drilling and reservoir engineering—are inherited from the oil, gas, and geothermal sectors and are already well established. Significant barriers remain, notably in terms of business models, regulatory frameworks, public acceptance, the integrity of legacy wells, infrastructure availability, and the long timelines required to characterise, qualify, and commission storage sites.

In this context, the development of pilot and demonstration sites is a critical step, especially for saline aquifers. In France, this approach was first illustrated by the Lacq—Rousse pilot project led by TotalEnergies. Between 2010 and 2013, approximately 51 kt of CO₂ was injected into the depleted Rousse gas reservoir, followed by post-injection monitoring until 2016, with seismic monitoring still ongoing. This project demonstrated the technical feasibility of an integrated CCS chain and enabled the development of methodologies for site qualification, monitoring, and long-term stewardship, while also supporting collaborative research with academic partners. However, this pilot did not lead to the establishment of additional onshore demonstration sites in France and remains the country’s unique reference for subsurface CO₂ injection. More recently, the cancellation of the PYCASSO project in 2024 highlighted the persistent challenges associated with scaling up, including uncertainties related to reservoir conditions, risk perception, competing uses of the subsurface, and local opposition.

Faced with these constraints, French industrial stakeholders are increasingly turning to European storage projects, most often located offshore. In the short term, the main destinations for French CO₂ emissions are in the North Sea and the Mediterranean. Key projects include Northern Lights in Norway, in which TotalEnergies is a partner, and Ravenna CCS in Italy, led by Eni and Snam. Other initiatives, such as Aramis in the Netherlands and Prinos in Greece, are also contributing to the structuring of a European CO₂ storage network. At present, most projects involving French emitters rely on access to storage capacities located outside France.

Nevertheless, the French government is now pursuing a dual strategy combining offshore storage in territorial waters with the development of onshore storage solutions, in order to address issues of sovereignty, industrial competitiveness, and transport cost reduction. In this context, the EVASTOCO2 study, published in 2025 and coordinated by BRGM in collaboration with IFPEN, the University of Lorraine, and industrial partners at the request of the DGECC, provides an assessment of France’s theoretical CO₂ storage capacities. It constitutes a reference framework for guiding further investigations and the potential deployment of demonstrators. The call for expressions of interest launched in 2024 mobilised a broad range of stakeholders, including 16 subsurface operators (hydrocarbon producers, geothermal operators, and energy companies interested in exploring dissolved-CO₂ injection into saline aquifers from geothermal installations) and 18 engineering and service companies specialising in subsurface activities (geological surveys, seismic acquisition, exploratory drilling, monitoring, and surveillance). This emerging dynamic also offers diversification opportunities for subsurface operators in the context of the planned phase-out of hydrocarbon production in France by 2040 (Hulot Law, 2017). A forthcoming call for projects (AgiBAC), to be launched by the SGPI, aims to support the development of onshore CO₂ injection demonstrators, which are essential for advancing scientific knowledge and technological readiness.

In this framework, research plays a central role in reducing uncertainties, qualifying storage sites, and preparing future demonstration projects. Key areas include reservoir characterisation, modelling of CO₂ injection and migration, fluid—rock interactions, geochemistry, geomechanics, monitoring strategies, long-term monitoring protocols, and data processing. The CNRS holds a recognised position alongside BRGM and IFPEN, notably through joint research units ■■■

■■■ such as GeoRessources and Géosciences Environnement Toulouse. This collaborative effort is reflected in initiatives such as the CO2ES, CARB3E, and CarMa research chairs, as well as in European programmes like PilotSTRATEGY and national programmes such as PEPR SPLEEN, which address onshore geological storage, long-term monitoring, and the socio-technical dimensions of its deployment.

French regional CCUS hubs

To achieve annual CO₂ capture volumes of 4 to 8 Mt from 2030 onwards, several industrial and port hub projects are under consideration (see table

below). These initiatives aim to establish fully integrated CCUS value chains in regions with high concentrations of emitters, including Dunkerque, the Rhône basin (Rhône Decarbonation project), the Loire Valley and Saint-Nazaire (GOCO2 project), and the Seine—Le Havre area. All these projects, currently under consideration as part of the Low-Carbon Industrial Zones (ZIBaC) initiative, share the common feature of offshore CO₂ storage outside France—primarily in the North Sea for Atlantic-facing regions and near Ravenna for Mediterranean areas. Consequently, they require the development of dedicated CO₂ transport infrastructure linking emission sites to port facilities.

Hub	DKarbonation (D'Artagnan, K6, CALCC)	Rhône-Decarbonation	Axe Seine	GOCO ₂
Zone	Dunkerque district	Rhône Valley — Fos-sur-Mer	Rouen - Le Havre	Western France and Saint-Nazaire
Main emitters	Lhoist (lime) Eqiom (cement)	Vicat (cement)	TotalEnergies and ExxonMobil (refining) Yara (fertilisers) Borealis (chemicals)	Lhoist (lime) Heidelberg Materials, Lafarge Holcim Ciments (cement)
Other industrial players involved (capture, transport, storage)	Air Liquide, RTE, Dunkerque LNG	SPSE, Elengy, ENI	Air Liquide, Haropa Port, NaTran	RTE, NaTran, Elengy
Planned final storage site	North Sea (Norway)	Mediterranean Sea (Ravenna, Italy)	North Sea (Norway or Denmark)	North Sea (Norway)
Estimated budget	€1.2 billion	€1.5 billion	€2.5 billion	€2.5 billion
Transport infrastructure	80 km of pipelines to be built	Existing pipelines; some connections to be provided	Pipeline network to be built from the source sites to the Seine	375 km of pipelines to be built
Annual CO ₂ capture targets	1.5 Mt then 4 Mt	1.2 Mt (with VICAT alone, then 4 Mt)	~7 Mt	2.6 Mt (2030) 4 Mt (2050)
CNDP public consultation	2023-2024	2025	-	2025

TECHNOLOGY INNOVATORS

In a technologically intensive field such as CCUS, the translation of scientific knowledge into industrial applications relies heavily on intermediary actors, here referred to as technology innovators. These entities are responsible for advancing building blocks derived from academic research to levels of technological maturity compatible with their integration into full-scale industrial systems. As highlighted throughout this report, CNRS research outputs are predominantly situated at low to intermediate Technology Readiness Levels (TRL 1–4). Achieving economic viability and large-scale deployment of disruptive technologies therefore requires a progressive increase in TRL over extended timeframes, typically about a decade. This critical phase of integration and scale-up generally lies beyond the remit of academic laboratories.

Moreover, CCUS research has not historically been structured as an integrated sector. Instead, it has evolved through well-established disciplinary domains—such as materials chemistry, catalysis, electrochemistry, process engineering, geology, and even the social sciences—each addressing specific segments of the value chain. This disciplinary fragmentation complicates system-level approaches, particularly when integrating process engineering considerations and industrial economic constraints. In this context, technology innovators play a pivotal role in bridging these gaps and facilitating knowledge transfer. Their contribution is especially strategic given the time pressures imposed by climate targets, which necessitate an accelerated maturation of the entire CCUS value chain.

In this context, IFPEN occupies a distinctive position. Building on a strong legacy in process and industrial engineering, it develops its own CO₂ capture technologies, notably the DMX process based on demixing amines. The development of this process, initiated

in the early 2010s, has followed a staged, scale-up approach: from laboratory experiments at very low flow rates (on the order of one gram of CO₂ per hour), to pilot-scale testing (kg/h), and subsequently to the deployment of a demonstrator operating at approximately one tonne per hour. The pilot phase enables the evaluation of overall process performance and solvent ageing, while the demonstrator phase is intended to establish design criteria for full-scale industrial implementation. The DMX demonstrator installed in Dunkerque between 2019 and 2024, in partnership with ArcelorMittal, exemplifies this approach. It enabled validation of the process under real industrial conditions at a steel plant, ahead of planned commercial deployment through IFPEN's subsidiary Axens. In parallel, another subsidiary, BEICIP, provides consultancy services in CCUS, including the identification of suitable storage sites. This integrated model—combining in-house development, demonstration, and commercialisation—distinguishes IFPEN from more traditional academic institutions such as the CNRS, whose activities remain predominantly focused on upstream scientific research.

On the other hand, large industrial groups tend to develop the core technologies underpinning their strategic priorities internally, drawing on academic research primarily for exploratory, forward-looking, or complementary topics. This division of roles contributes to a system in which coordination across the overall CCUS value chain remains limited.

At the same time, specialised SMEs—and, to a lesser extent, certain mid-sized companies—play a key role by operating in targeted segments of the CCUS value chain, including engineering, equipment manufacturing, instrumentation, feasibility studies, and process integration. They contribute to bridging the gap between research outputs, pilot and demonstration phases, and industrial deployment. Their activities are increasingly supported by recent public funding

schemes such as the IBaC PME and DEMIBaC calls for projects, led by ADEME under the France 2030 programme, which aim to foster the development of technological building blocks and demonstrators across companies of various sizes.

Start-ups occupy a distinct niche, advancing technologies that are still too immature or risky to attract immediate investment from large industrial players. As noted in the 'Research Outputs' chapter (page 37), their number remains relatively limited in France—particularly within the CNRS ecosystem—although a noticeable increase has been observed since 2018 in the CCUS domain. These young companies typically focus on disruptive technological building blocks emerging from recent academic research. In the field of CO₂ capture, for example, Revcoo (not originating from the CNRS) and Cryopur (a spin-off from Mines ParisTech, now part of La Française de l'Énergie) have developed capture processes based on anti-sublimation, enabling the production of high-purity CO₂ even from streams with low initial concentrations.

Start-ups originating from the CNRS tend to focus more specifically on CO₂ utilisation, leveraging cutting-edge expertise derived from academic research, particularly in areas such as CO₂ electrolysis, plasma catalysis, and other advanced electrochemical processes. Companies such as Dioxycle and, more recently, E-ETHYLENE illustrate this trend: they build on recent scientific advances to develop devices capable of converting CO₂ into ethylene, with the objective of overcoming key technological barriers on the path to pilot-scale deployment. Similarly, start-ups such as Carboneo (founded in 2020) are developing electrochemical cells dedicated to CO₂ electrolysis.

Several other start-ups active in CO₂ utilisation are also noteworthy:

- Energo Green focuses on CO₂ derived from biogas produced from agricultural waste (e.g. manure, slurry, and other residues). This CO₂ is first liquefied and then converted, via a plasma-electrolysis process, into methane or methanol. The longer-term objective is the production of e-kerosene for direct supply to the aviation sector at airports. As this fuel is entirely derived from biogenic carbon, it complies with the European e-SAF directive. The company's model relies on small-scale, high-efficiency units (approximately 1,000 m³/h) located in close proximity to feedstock sources, thereby minimising transport requirements, limiting land use, and benefiting from access to low-carbon and comparatively affordable energy in France.
- Mecaware, as noted earlier, uses CO₂ in processes for recycling critical metals—particularly those recovered from batteries (nickel, manganese, cobalt, lithium). By converting these metals into carbonates, the process both incorporates CO₂ into stable materials and avoids the use of sulphate-based routes.



In a technologically intensive field such as CCUS, the translation of scientific knowledge into industrial applications relies heavily on intermediary actors, here referred to as technology innovators.

Finally, although direct air capture (DAC) lies outside the main scope of this study, it provides a useful point of comparison. The underlying scientific principles—such as the use of porous materials, selective adsorption, and energy optimisation—are similar to those in CCUS, but applied to much lower CO₂ concentrations. DAC is often highlighted for its flexibility, as systems can be deployed in a wide range of locations, including near energy sources, industrial facilities, or storage sites. However, the most advanced DAC approaches typically rely on thermal processes to release captured CO₂ and regenerate adsorbents. As these steps are energy-intensive, the overall carbon balance can be unfavourable if low-carbon energy sources are not used. For example, Climeworks, a Zurich-based company often considered a leader in the field, employs a process in which air is passed through filters composed of cellulose-based materials functionalised with amines. However, its reported 2025 performance highlights the challenges of DAC, with a net positive emissions balance. This underscores the importance of coupling DAC systems with low-carbon energy sources—either inherently, as in the case of Climeworks’ use of geothermal energy, or by integrating carbon capture into the energy supply itself, as pursued by Carbon Engineering. Among emerging approaches, DAC technologies based on MOFs appear promising, although they remain at relatively low Technology Readiness Levels. The CNRS has been active in this field since the 2000s, notably through the work of Gérard Férey. This research continues today, particularly with Karim Adil and Amandine Cadiau, who are developing fluorinated-pillar MOFs of interest due to their high chemical and thermal stability, strong resistance to moisture and H₂S, and high selectivity for CO₂. While the spin-off Stathmos is exploring DAC applications based on such materials, their cost and synthesis remain significant barriers to large-scale deployment.

The role of these start-ups is strategic, as they explore high-risk technological pathways that large industrial groups typically only engage with at more advanced stages. In doing so, they contribute to the emergence of potentially disruptive solutions in the medium term. However, several interviewees pointed to a structural gap in France in terms of funding for pilot and demonstrator phases, as well as a comparatively less developed culture of process engineering at the research stage than in other industrialised countries, such as Germany (notably through the Fraunhofer Institutes), the United Kingdom, or China. This context may partly explain both the relatively limited number of start-ups in the field and the challenges associated with rapidly translating scientific advances into deployable industrial solutions.

ADVISORY AND ADVOCACY BODIES

In France, stakeholders across the CCUS value chain have structured their activities through dedicated organisations, notably the Club CO₂ and the French Association for Negative Emissions (AFEN). Established in 2002, the Club CO₂ focuses broadly on CCUS, whereas AFEN specialises in carbon dioxide removal (CDR)¹². These organisations act as platforms for knowledge exchange, awareness-raising, and dialogue among industry, academia, investors, and public authorities. They also produce studies and position papers aimed at informing their members, sectoral strategic committees, the Energy Regulatory Commission, and government bodies such as the Directorate General for Enterprise (DGE). Recent publications have addressed topics such as the mapping of CDR potential in France, employment prospects in the CCUS sector, regulatory frameworks for CCS infrastructure, and overviews of CO₂ utilisation pathways.

12. CDR refers to approaches aimed at permanently removing CO₂ from the atmosphere. It differs from CCUS, which focuses on capturing CO₂ at source; however, the two concepts overlap when captured CO₂ is of biogenic origin and subsequently stored.

At a European level, the CO₂ Value Europe association brings together more than 100 organisations from all around the world and across a wide range of sectors (including industry, start-ups, universities, research and technology bodies, and regional clusters) and develops forums for discussion, policy analysis and databases to help the EU achieve its climate targets.

In parallel, a growing number of consulting firms specialising in sustainable development and energy transition have emerged over the past two decades, some of which have developed specific expertise in CCUS. These firms are primarily based in the United States, the United Kingdom, Sweden, Germany, Australia, and Canada. However, several French consultancies—such as Alcimed, Sia Partners, E-Cube, Yélé Consulting, and Carbone 4—are also active in this field. Their services include tailored analyses, multi-scale market studies, strategic advisory, as well as support for governance and organisational transformation.

STAKEHOLDERS IN THE PUBLIC DEBATE

The societal acceptance and appropriation of an industrial project result from a collective process involving project developers, elected representatives, public authorities, and citizens, including local residents and civil society organisations. For an emerging industrial sector such as CCUS, it is therefore essential that all stakeholders have access to clear and comprehensive information in order to fully understand the associated challenges.

However, CCUS has so far received limited public communication from authorities, industry, the scientific community, and the media. A common feedback from public consultations organised by the National Commission for Public Debate (CNDP)¹³ on the GOCO2 and Rhône Décarbonation projects is “the difficulty in grasping, both in technical and economic terms, a value chain encompassing CO₂ capture, transport, liquefaction, and geological storage, which has only been successfully deployed at industrial scale worldwide in 2025, and was not known to the public”.



“ It appears difficult to grasp, both in technical and economic terms, a value chain encompassing CO₂ capture, transport, liquefaction, and geological storage, which has only been successfully deployed at industrial scale worldwide in 2025, and was not known to the public. ”

13. The CNDP (Commission Nationale du Débat Public) is an independent authority that guarantees the public’s right to information and participation in the development of projects and public policies with environmental impacts. This right is enshrined in Article 7 of the French Environmental Charter. The CNDP is mandatorily consulted for major projects and may also be involved on a voluntary basis for projects with more limited impacts (<https://www.debatpublic.fr/en>).

As noted by the NégaWatt association (Christian Couturier, October 2025), drawing on IPCC scenarios, “rapid reductions in gross emissions must remain the priority; CDR solutions, including CCS, can accelerate this reduction.” At the same time, “Europe’s geological CO₂ storage capacity is estimated at around 100 GtCO₂, while annual emissions still amount to approximately 2.5 GtCO₂.” No credible scenario suggests that biological reservoirs alone (forests, agricultural soils, wood products) can offset emissions, particularly given the increasing vulnerability of these reservoirs to climate change. CCS is therefore likely to be necessary, but not sufficient, to achieve climate neutrality. Concerns that CCS might serve as a “silver bullet” allowing industry to avoid structural transformation are not supported by current scenario analyses.

Beyond these general considerations, each component of the CCUS value chain is subject to scrutiny and debate from associations, think tanks, professional organisations, and local stakeholders. Public consultations for projects such as GOCO2, Rhône Décarbonation, and CAP Décarbonation have consistently called for comprehensive assessments of overall carbon footprints and life-cycle impacts. Such analyses could provide valuable guidance for industrial decision-making, particularly in the selection of capture technologies. The transport of CO₂ by pipeline raises questions, though not necessarily outright opposition, especially among agricultural stakeholders. Concerns relate to route selection, the impact of construction on hedgerows and biodiversity, the long-term integrity of infrastructure, and the risks associated with leaks or temporary storage. In this context, intermediary bodies such as chambers of agriculture can play an important role in facilitating dialogue between project developers and affected communities. “Geological storage remains the most debated component of CCUS projects.

Discussions focus on the technical modalities of storage, its permanence or reversibility, its economic viability, and the availability of suitable (often offshore) storage sites. Issues of national sovereignty may also arise. While the long-term integrity of storage is frequently questioned, some concerns stem from broader perceptions of risk associated with this stage of the value chain”. Several stakeholders refer to the failure of the PYCASSO project as evidence of limited societal acceptance of geological storage. However, this interpretation is incomplete: the primary issue was not storage safety, but the proposed change in use of gas fields currently exploited by the chemical industry—an activity considered essential for local employment and economic stability by elected authorities, trade unions, and industrial actors. Moreover, according to one interviewee, “social acceptability was used as a pretext, as no genuine public debate had taken place.”



The discussions also underscore the need to clarify the role assigned to CO₂ utilisation, particularly in the context of e-fuel production for aviation. As the CO₂ used for synthetic aviation fuels (e-SAF) will increasingly need to originate from non-fossil sources, the use of CO₂ derived from industrial emissions implies a near-complete decarbonisation of upstream processes. As highlighted in a recent report by The Shift Project and AeroDécarbo, “SAF production, both in France and globally, will be constrained by physical and industrial limits, as well as by competing uses of sustainable biomass and low-carbon electricity”.

While public debates reveal clear concerns regarding the economic models underpinning CCUS projects—particularly the scale of public funding allocated to private actors—associations and think tanks generally do not contest the need for public support. Such support is viewed as necessary to maintain industrial competitiveness, regional economic activity, and employment, provided that it is conditional upon achieving the highest possible level of decarbonisation upstream of CCUS processes.



Framing the transition solely as a choice between technological solutions and demand reduction is too simplistic; effective strategies must be grounded in robust data on current emissions and the transformations required for meeting carbon neutrality targets by 2050.

More broadly, citizens’ perspectives highlight the importance of fostering a comprehensive and well-informed public debate on decarbonisation pathways and the role of public authorities in achieving net-zero emissions. A limited understanding of CCUS and its function within broader decarbonisation strategies is also evident within the political sphere, including in parliamentary debates, which complicates the adoption of clear policy positions. Framing the transition solely as a choice between technological solutions and demand reduction is too simplistic; effective strategies must be grounded in robust data on current emissions and the transformations required for meeting carbon neutrality targets by 2050.

TRAINING INSTITUTIONS OR ORGANISATIONS

The development of the CCUS sector will generate substantial demand for specialised skills. However, no comprehensive study has yet identified the key professions required, either qualitatively or quantitatively. Addressing these needs will require coordinated efforts across academic institutions and private actors, including continuing education providers and industry. Several organisations are already engaged in this effort: IFPEN and BRGM, along with companies such as Teréga, offer continuing professional development programmes for engineers and technicians. In parallel, researchers from CNRS joint research units (UMRs) contribute to initial training through university and engineering curricula and have supported the training of future sector leaders through the supervision of nearly 115 doctoral theses.

THE MEDIA

Media coverage of CCUS has evolved in line with shifting levels of public and policy interest. Data from the Factiva and Europress databases indicate that, since 2005, the French-language press has published several hundred articles annually on the subject, primarily in major daily newspapers (both print and online). After a decline in the mid-2010s, media attention has increased sharply since 2018, with more than a thousand articles published per year. These articles typically question the relevance and prospects of CCUS technologies, report on emerging industrial projects in France (e.g. TotalEnergies, ArcelorMittal, Air Liquide), and cover national strategic initiatives, particularly since 2023. Scientific research, however, remains only marginally represented, accounting for approximately 4% of articles. Nevertheless, more than 500 articles mentioning the CNRS were published between 2005 and 2025, out of roughly 13,000 articles on CCUS overall. Since 2019 (excluding the pandemic year 2020), this corresponds to more than fifty such articles per year.

In France, media coverage is primarily concentrated in national press, print and online, notably Le Monde (49 articles), Les Échos (27), Le Figaro (27), Usine Nouvelle (32), La Tribune (29), and La Croix (16). This is followed by regional newspapers: L'Est Républicain (11), Sud-Ouest (13), and Ouest-France (7). More specialised publications also contribute to coverage, such as Science et Avenir (23) and the Journal de l'Environnement (10), alongside dispatches from Agence France-Presse (20).

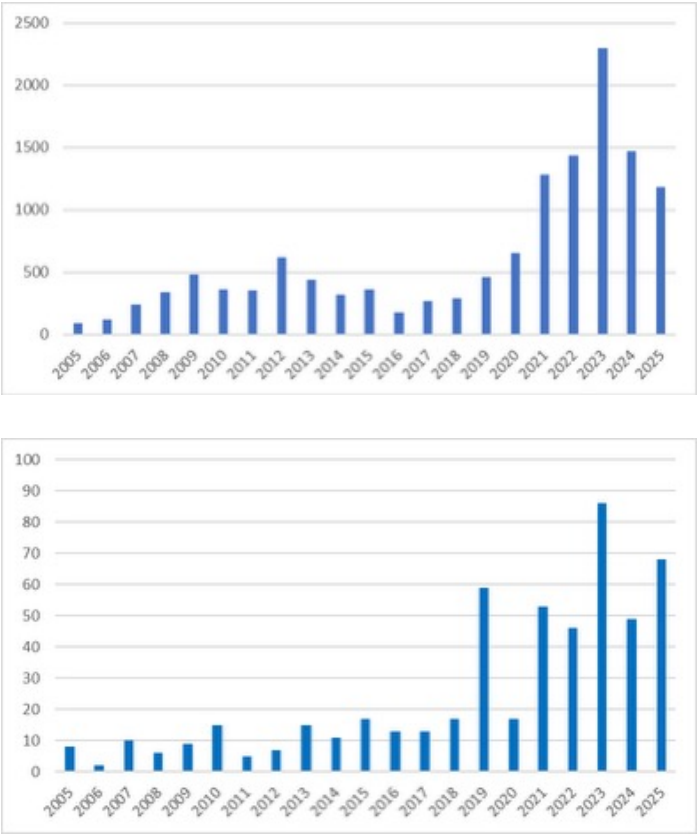


Figure 14: Number of articles identified in the French-language press relating to CCUS overall (top) and specifically mentioning the CNRS (bottom).
(sources: Factiva and Europress press databases)



IMPACTS

Conceptually, the impact of research should always be evaluated relative to a counterfactual scenario, that is, by comparison with a situation in which the research had not been conducted. In this study, we categorize impacts as already observable or proven, those initiated or expected in the near term, and those anticipated or hoped for.

It is important to emphasise that this analysis focuses on the societal impact of research, rather than on the societal impact of CCUS technologies themselves. Given that no fully operational CCUS industrial sector currently exists in France, the societal effects of this research remain, at this stage, largely indirect or not yet observable.

SCIENTIFIC IMPACT (expected impact)

The scientific impact of research conducted by the CNRS and its partners on CCUS spans a broad range of disciplines. However, within a highly fragmented landscape, this impact remains difficult to assess. CCUS does not constitute a single, coherent scientific field, but rather encompasses a set of heterogeneous disciplines and technologies which, although present within laboratories, tend to interact only marginally. This structural fragmentation contributes to a relatively weak organisation of the CCUS research community

and to limited institutional coordination. In this context, the PEPR SPLEEN programme, launched in 2023, is widely recognised by stakeholders as playing a key role in structuring the scientific landscape and coordinating research themes. Nevertheless, links with industrial actors remain relatively limited, despite ongoing efforts. Similarly, while Club CO₂ provides a forum for regular exchanges among stakeholders, academic participation appears to be modest.

More broadly, several obstacles to increasing technology readiness levels (TRLs) have been highlighted, including a shortage of pilot plants and demonstrators—many of which are being developed internationally, often to the detriment of French research—and insufficient coordination within the CNRS between chemistry and chemical engineering communities, which are managed by different CNRS institutes.

Despite these limitations, the potential scientific impact of CNRS research is expected to be substantial across all segments of the CCUS value chain. Key technological options remain open, and their development will depend heavily on upstream research (TRL 1–3) conducted in academic laboratories and ‘awaited’ by industry. **The following points can thus be noted for the various components of CCUS:**

- **Capture:** in the short term, efforts will focus on improving amine-based solvents currently used in commercial processes, particularly with regard to efficiency, energy consumption, stability, and toxicity. Beyond compositional optimisation, further work is still required on process configurations—such as phase-separating systems, precipitating solvents, and membrane contactors—areas in which laboratories such as LRGP (Nancy) are particularly active. In the medium term, alternative capture technologies operating at lower temperatures and with improved performance are expected to emerge, notably based on porous solid materials. This is a highly dynamic research area within the CNRS, involving laboratories such as IMAP (Paris), IJL (Nancy), IRCELYON, CP2M and LAGEPP (Lyon), UCCS (Lille), ICPEES (Strasbourg), CRPP (Bordeaux), and IMN (Nantes), as reflected in a substantial body of publications and patents. Research on selective membranes for flue gas separation is also particularly active, for example at IEM (Montpellier). By contrast, technologies for cryogenic capture, desublimation, and CO₂ liquefaction remain largely driven by industry, with limited involvement from

CNRS laboratories, particularly as their sensitivity to pollutants and their high energy requirements raise questions about their use as a long-term solution. Finally, there is a growing need to develop capture processes based on electrified systems, in order to avoid indirect reliance on fossil energy sources. Enhancing the operational flexibility of capture technologies is also critical, so that they can better accommodate the dynamic operating conditions of industrial facilities, which often evolve more rapidly than conventional chemical absorption systems can respond.

- **Utilisation:** this dimension is addressed, at least from an academic perspective, within the axis 4 of the PEPR SPLEEN programme, entitled “CO₂ Storage and Utilisation.” In this field, the CNRS is a major international contributor as it is one of the world leaders in the electrochemical CO₂ reduction (with laboratories such as IPCM Paris, CPB Paris, ICBMS Lyon, ICMPE Thiais, IEM Montpellier, LCBM Grenoble, and LRGP Nancy), as well as the concrete carbonation (with LMGC Montpellier, LSCE Versailles, LGC Toulouse, LaSIE La Rochelle) and biological capture using microorganisms (with TBI and LISBP Toulouse, BIP Marseille, LPCV Grenoble). As such, the CNRS is well positioned to drive significant advances in CO₂ utilisation, including at industrial scale, in the coming years.

- **Storage:** although geological storage is only marginally addressed within the PEPRs SPLEEN and “Sub-surface: a common good” programmes, high-level research on subsurface storage is conducted within several CNRS laboratories, including LGENS (Paris), Géosciences Montpellier, Géosciences Environnement Toulouse, Géoressources (Nancy), and LOG (Wimereux). These activities complement the work on chemical and mineral storage pathways described previously (see the ‘Research Outputs’ chapter page 30).

● **Public debate and societal acceptability:** while the PEPR SPLEEN programme does not address the technological and physico-chemical aspects of CO₂ storage, it does focus on the socio-technical conditions required to identify and develop onshore storage sites in France. Several CNRS laboratories are therefore engaged in analysing the social, political, and territorial dimensions of CO₂ storage, including TREE (Pau), PACTE (Grenoble), and CIRED (Nogent-sur-Marne). This body of work is expected to have a significant societal impact on the analysis of the conditions for deploying CCUS.

In the shorter term, research conducted by the CNRS and its partners could also have a tangible impact on key barriers to the sector’s economic development, particularly those linked to current technological limitations. For example, corrosion in transport pipelines caused by nitrogen and sulphur oxides—an issue with direct implications for regulatory standards—is not currently addressed within existing PEPR programmes, yet it is a recognised area of expertise within several CNRS laboratories (IRCP Paris, CIRIMAT Toulouse, CEMHTI Orléans, CRISMAT Caen). Similarly, the monitoring of geological storage sites remains insufficiently covered by current programmes, despite its strategic importance. This topic could be further developed by CNRS, particularly in light of the large volumes of data that long-term monitoring will generate and the associated challenges in data processing and interpretation. Finally, issues related to public debate, social acceptability, and societal appropriation remain central. Although the research conducted on CCUS is recognised and valued by a wide range of stakeholders—across economic, political, and civil society spheres—it is still perceived as insufficiently

developed in these areas. As one stakeholder notes, *“this is a major issue because, beyond the preliminary consultations, public consultations and inquiries that affect the granting of building and operating permits, I have observed that the public’s limited understanding of these issues and solutions leads to significant political consequences. When environmental policies and the associated financial resources are not clearly understood, European governments face a backlash of protest votes toward the extremes”* (E. Bourdon, Vicat).



“ When environmental policies and the associated financial resources are not clearly understood, European governments face a backlash of protest votes toward the extremes. ”

ECONOMIC IMPACT

To assess the economic impact of research conducted at the CNRS on CCUS between 2005 and 2024—and not, more broadly, the direct economic impact of all academic research or of the CCUS sector as a whole—three lines of analysis were examined:

- 1 **TECHNOLOGIES ARISING FROM PATENTS** co-owned with the CNRS,
- 2 **THE DEVELOPMENT OF COMPANIES** whose core technology originates from CNRS research,
- 3 **REVENUE GENERATED BY PRESS ARTICLES** mentioning CNRS research on CCUS

Beyond these direct effects, once CCUS is deployed at industrial scale, it will also be necessary to consider indirect impacts, particularly those linked to companies that use these research results to strengthen regional economic development and industrial attractiveness.

PATENT REVENUE (expected impact)

As noted above, around ten patent families have already been transferred to SMEs or start-ups, particularly in the fields of MOFs and CO₂ reduction. However, these agreements are still very recent, with most concluded within the last five years. Moreover, the revenues generated by these patents—on the order of €15,000—and the turnover currently associated with them remain too limited to indicate a significant economic impact at this stage. More substantial benefits are nevertheless expected as future products and processes reach the market.



REVENUE AND JOBS GENERATED BY CNRS SPIN-OFFS AND COMPANIES USING CNRS-DEVELOPED PROCESSES (expected impact)

Since 2018, eight start-ups have emerged from, or are affiliated with, CNRS laboratories. In parallel, some technologies co-developed by CNRS laboratories and industrial partners now underpin innovative companies. Although these entities are still recent, some have already evolved into SMEs with strong growth potential. Based on the available financial data for these CNRS-linked entities—whether publicly disclosed or obtained through confidential communications—it is possible to estimate their current revenues and projected growth through 2028, alongside direct jobs created:

YEAR	JOBS	TURNOVER (€ MILLION)
2025	110-150	1
2028	~ 300	~ 120

MEDIA COVERAGE (proven impact)

As noted above, research conducted at the CNRS on CCUS has generated nearly 1,000 press articles between 2000 and 2025, including 520 in the French-language press. Based on an average revenue of approximately €9,200 per article on this topic (see Appendix 1 for the methodology), the total media revenue associated with articles mentioning CNRS research on CCUS exceeds **€9.6 million** worldwide, of which **€4.8 million** is attributable to the French press.

SUMMARY AND OUTLOOK

In 2025, the revenue generated by CNRS research on CCUS therefore remains modest, at around €10 million, but it could rise to at least €130 million by 2028. Compared with the total financial investment of €400 million (see balance sheet, page 27), the return on investment is currently negative. Nonetheless, the recent government’s momentum in favour of CCUS should support broader industrial deployment by 2030 and, in turn, a gradual increase in the development and uptake of research outputs and breakthrough innovations.



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POLITICAL AND REGULATORY IMPACT (expected impact)

Although a large majority of stakeholders now recognise the central role of CCUS in meeting national and European CO₂ reduction targets, the environmental reach of the sector remains severely constrained by the absence of a viable business model in the short term. In the near future, the main levers for enabling CCS deployment will be restrictive regulation, public co-funding, and an appropriate carbon price, provided these instruments are implemented in a coordinated way. Regulation alone, without public support, would at best preserve the current emissions trajectory if carbon prices remain low, and at worst encourage industrial relocation. As for CO₂ utilisation, its long-term prospects appear strongest in materials applications, since e-fuel development will increasingly depend on biogenic carbon.

In this context, research conducted at the CNRS and its partners will be crucial for

- 1

OPTIMISING CO₂ CAPTURE in terms of cost, emissions, and performance;
- 2

DEVELOPING UTILISATION PROCESSES that are less energy- and water-intensive, and therefore more economically viable;
- 3

LEVERAGING SUBSURFACE KNOWLEDGE to improve long-term monitoring methods and strengthen data processing capabilities;
- 4

FACILITATING SOCIETAL ACCEPTANCE of this emerging industrial sector, whether with regard to its role in the decarbonisation pathway, safety issues (transport pipelines, storage), the need for public funding, or broader social implications. In the view of all those interviewed, public debates should be analysed, objectified, and, where appropriate, co-constructed by scientists from CNRS joint research units in the humanities and social sciences.



However, it should be noted that, to date, scientific stakeholders have generally been excluded from the mechanisms used to define national acceleration strategies. Thus, the first CCUS steering committee, held in February 2026, brought together political and industrial leaders without any scientific representation. According to several interviewees, the scientific input informing central government decisions on CCUS comes indirectly through industry, associations, and think tanks—many of which themselves rely on scientific data—but not directly from scientists or their institutional representatives. While it is legitimate that scientific stakeholders are not decision-makers, their role is to inform public debate and policy choices by providing an objective and independent perspective. The strength of scientific institutions lies precisely in their impartiality. This observation, already made in the impact assessment of CNRS research on batteries¹⁴, echoes the limited presence of scientific evidence in French strategic documents, in contrast to the strategic documents produced by the European Commission and by countries such as Germany and the United Kingdom. In the case of CCUS, an emerging industrial sector, economic and scientific stakeholders have complementary and mutually reinforcing roles, and this is widely acknowledged by both sides. The key question is therefore which levers should be activated to ensure that science more effectively informs public policy on CCUS. Should the CNRS become more involved in Club CO₂? What role should the French Programm Agency for Low Carbon Energy (APED) play? These are important questions that must be addressed if research, industrial development, and public policy are to work in concert toward decarbonisation targets.



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14. https://www.cnrs.fr/sites/default/files/page/2025-12/CNRS_SOCIETAL%20IMPACT%20STUDY_BATTERIES.pdf

ENVIRONMENTAL IMPACT (expected impact)

By design, the CCUS value chain is intended to reduce environmental impacts, as it constitutes one of the final levers available to industry for lowering CO₂ emissions. According to ADEME, if all projects currently under development by cement manufacturers—the most advanced sector in terms of CO₂ capture—were implemented, annual capture could reach 1.2 MtCO₂ by 2030, out of the 4 to 8 MtCO₂ projected in the French roadmap. However, it remains essential that CCUS itself does not compromise environmental objectives, particularly with regard to energy and water consumption, and, to a lesser extent, land use. This requirement must nevertheless be balanced against the fact that, all things considered, the cost of inaction on reducing GHG emissions is immeasurable.

In this perspective, the different components of CCUS still leave considerable room for improvement, and this is precisely the focus of several ongoing research efforts. CO₂ capture processes are energy- and water-intensive. Through its DMX process, commercialised by Axens, IFPEN has sought to reduce this energy penalty. At present, capturing one tonne of CO₂ at the plant outlet requires approximately 2 to 3 gigajoules of energy, compared with around 10 gigajoules for direct air capture. Research on membranes, porous

solids, and MOFs—particularly for low-CO₂-concentration sources—together with progress in life-cycle assessment across the entire CCUS chain, now routinely carried out, is helping to improve environmental performance. In the long term, these developments should make capture processes more efficient and, in the case of biogenic or atmospheric CO₂, may even enable negative emissions, provided that the relevant industrial sectors are effectively deployed and continue to generate demand for technological innovation. Such progress is essential if CCUS is not to be dismissed as a form of techno-solutionism that merely preserves an existing production model, but rather recognised as the necessary final step in accelerating industrial decarbonisation.

The same applies to CO₂ utilisation pathways, which also raise substantial environmental questions. Some catalysts rely on rare metals, and the production of one tonne of e-fuel requires roughly 5 tonnes of CO₂ and 0.7 tonnes of hydrogen, produced by the electrolysis of 6.5 tonnes of water and consuming about 40 MWh of electricity (see Figure 15).

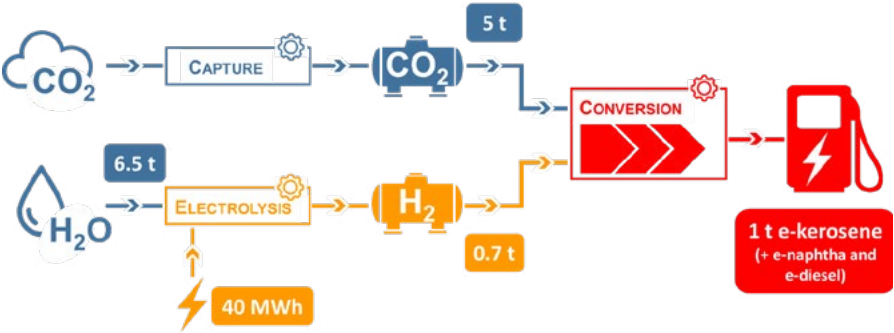


Figure 15: Schematic diagram of e-fuel production.

(source: CEA/IFPEN factsheet 'Towards a First E-Fuel Production Chain')

SOCIAL IMPACT

More broadly, CNRS research is guided by the principle of energy efficiency, which is a key condition for progress in technology readiness levels (TRLs). This applies both to the use of concentrated natural light and to LED-based approaches aimed at reducing the energy cost of CO₂ reduction. Start-ups originating from CNRS research, such as Mecaware, Energo, and Dioxycle, likewise build their models on the energy efficiency and sustainability of their chemical processes. In addition, the recent discovery by the CNRS and the University of Lorraine of a substantial reserve of natural hydrogen dissolved in groundwater in the Moselle region opens up prospects for producing e-fuels from CO₂ using less energy and water. Finally, carbonated concrete offers a pathway to producing dense, durable materials capable of storing CO₂ over the long term.

Whether in academic research or in start-up development, the activities underway are already offering concrete responses to the challenges of reducing energy costs, ensuring sustainability, limiting risks, and securing resources. Although these lines of work remain at different stages of maturity and still face several barriers before reaching higher TRL levels, they already demonstrate the relevance and coherence of the CNRS's scientific priorities.

Social impact is primarily assessed in terms of employment effects. A prospective study by Club CO₂ indicates that the development of the CCUS sector in France could generate between 200,000 and 400,000 jobs by 2050, depending on the scenario, with approximately 50% being direct employment. These jobs are expected to be largely temporary, as they are associated with infrastructure development and construction, with a peak anticipated around 2035. Long-term employment related to facility operation (including operators and maintenance personnel) is estimated at between 12,000 and 55,000 direct and indirect jobs, with growth expected after 2030¹⁵. These positions are mainly linked to carbon capture activities, followed by storage and utilisation. In contrast, transport is expected to generate relatively few long-term jobs, apart from those associated with the construction of CO₂ pipeline infrastructure.

If the CCUS sector reaches full industrial maturity, it could also contribute to preserving employment in carbon-intensive industries. In the absence of viable decarbonisation solutions, such industries may otherwise relocate production outside Europe to regions with lower energy costs and less stringent regulations. Conversely, CCUS deployment may, in some cases, negatively affect local employment, particularly where existing activities are replaced. This is notably the case when hydrocarbon reservoirs are repurposed for CO₂ storage rather than production, as observed in the Lacq basin; this transition likely contributed to the failure of the PYCASSO project.

In this context, the social impact directly attributable to CNRS research remains relatively modest at present. Job creation through CNRS spin-off start-ups may occur but is expected to remain limited to a few hundred positions. In the short term, these opportunities

mainly concern engineers and research engineers involved in pilot-scale projects. CNRS laboratories also contribute to social impact through training via research. Over time, these activities could support the development of a workforce already familiar with industrial requirements—particularly in electrical engineering, mechanical engineering, industrial IT, and assembly—that may help enhance the attractiveness of regions currently experiencing industrial decline. In the longer term, CNRS research on CO₂ utilisation could generate more substantial employment if sectors such as e-fuels, e-chemistry, and low-carbon materials achieve viable economic models and scale up.

Should electrolysis-based e-fuel projects—some led by CNRS teams—reach sufficient maturity, job creation could extend across the entire value chain, including the hydrogen sector that underpins these utilisation pathways (e.g., e-kerosene and power-to-liquid fuels).

Beyond quantitative employment effects, the most striking social impact lies in demonstrating that industrial development and environmental objectives can be reconciled, thereby contributing to the transition toward a more sustainable society.

At this stage, the study does not identify any direct or clearly attributable cultural or health impacts associated with CNRS research on CCUS..



15. <https://www.club-co2.fr/documents/storage/documents/2025/04/Club-CO2-Etude-Emploi-Synthese-publique.pdf>

Appendices

APPENDIX 1: METHODOLOGIES USED

Unless otherwise specified, all monetary values presented in this study are expressed in real terms (i.e. not adjusted for inflation).

1. ESTIMATION OF THE WAGE BILL

Since 2012, the CNRS has conducted annual or biennial “Energy” surveys across its laboratories. These surveys provide detailed data on full-time equivalent (FTE) staff by research area, including the share of personnel funded by the CNRS, the corresponding total payroll (including CNRS-funded staff), and the resulting average full-cost salary per year. They also include information on operating, equipment, and investment expenditure (FEI). In the table below, data directly derived from the surveys are presented in black, while extrapolated values are indicated in red.

Year	Total FTE	CNRS FTE	% CNRS	Total FTE on CCUS	CNRS FTE on CCUS	Total CNRS payroll on energy (M€)	FEI energy (M€)	Average salary (k€/year)	CNRS payroll on CCUS (M€)	Total payroll on CCUS (M€)
2012	7436	2251	30,3	141	43	145	31	64,4	2,7	9
2013	6812	1803	26,5	243	64	116	28	64,5	4,1	16
2014	5987	1625	27,1	206	56	109,37	28	67,3	3,8	14
2015	5538	1568	28,3	196	55	105	25	67	3,7	13
2016	5856	1592	27,2	156	42	105,26	23,75	66,1	2,8	10
2017	4546	1285	28,3	137	39	89,5	28	69,6	2,7	10
2018			28,2	153	43		27	70	3	11
2019	3713	1061	28,6	169	48	82	17,6	77,2	3,7	13
2020	4760	1394	29,3	238	70	108	26	77,5	5,4	18
2021			28,2	255	72		25	81,25	5,8	21
2022	4998	1425	28,5	272	78	121	25	85	6,6	23
2023			30	307,5	92	136,5	28	85	7,8	26
2024	5692	1809	31,8	343	109	152	31	84	9,2	27
Total or average	55338	15813	28,2	2816,5	811	1180,13	345,35		61,5	210,8
							Part CCUS: 17 M€			



As reliable data are not available for the period 2000—2011, estimates were made as follows:

- The annual full-cost salary was estimated by accounting for changes in the salary index between 2000 and 2011.
- Changes in the number of FTEs in the CCUS field were estimated on the basis of publication trend.
- The share of staff paid by the CNRS in the laboratories was set at 28.2%, corresponding to the average observed between 2011 and 2023.

Year	2011	2010	2009	2008	2007	2006	2005	Total
Number of publications	47	36	43	26	18	20	14	
Total FTE	172,6	132,2	157,9	95,5	66,1	73,4	51,4	749,1
CNRS FTE	48,7	37,3	44,5	26,9	18,6	20,7	14,5	211,3
Avarage salary	64,4	64,4	63,9	63,4	63,1	62,6	61,5	
Total payroll	11,1	8,5	10,1	6,1	4,2	4,6	3,2	47,7
CNRS payroll	3,1	2,4	2,8	1,7	1,2	1,3	0,9	13,5

In summary, the total payroll of CNRS laboratories involved in CCUS can be summarised as follows:

Years	Cumulative total FTE	Cumulative CNRS FTE	Total payroll (M€)	CNRS payroll (M€)	FEI (M€)
2005-2011	749,1	211,3	47,7	13,5	4,4
2012-2024	2816,5	811	210,8	61,5	17
2005-2023	3565,6	1022,3	258,5	75	21,4

2. LEXICAL QUERY FOR BIBLIOMETRICS

To identify CCUS scientific publications and technology patents, this study drew on preliminary work carried out in 2024 by VIA INNO, the University of Bordeaux's research platform (<https://www.viainno.fr>), as part of a study conducted for Club CO₂. With Club CO₂'s permission, for which we are grateful, VIA INNO provided the corpora it had compiled. We adapted these corpora for our own study in order to narrow the scope, given differences in how the CCUS field was defined.

VIA INNO's study is based on the construction of corpora using a search query developed in collaboration with experts from Club CO₂. This is followed by a data-cleaning stage based on lexical content, namely titles and abstracts, using artificial intelligence tools and then validated by the experts. After reviewing the submitted corpora, we narrowed the thematic scope of both the scientific publication corpus and the patent corpus to align them with our research topic by excluding documents related to biogenic carbon. To this end, we removed all documents whose titles contained any of the following terms: forest, plantation, vegetation, wood, crop, agriculture, biomass, biochar, ocean, mangrove, peatland, and wetland. We then retained VIA INNO's classification into four partially overlapping clusters—capture, utilisation, storage, and transport—based on lexical analysis. A single document may be assigned to more than one of these sub-themes.

For scientific articles, VIA INNO conducted the lexical search in the Scopus database (Elsevier), focusing on documents classified as “articles.” For technology patents, the search was carried out in the Orbit database (Questel) using a combination of keywords and CPC (Cooperative Patent Classification) codes.

3. ESTIMATION OF REVENUE GENERATED BY THE PRESS

The estimate of the average revenue generated by an article mentioning CNRS research on CCUS is based on a sample of 236 press articles from prominent French media outlets such as Le Monde, Les Echos, Le Figaro, La Tribune, Usine Nouvelle, AFP, Sud-Ouest, Ouest-France, La Croix, and Sciences et Avenir. It is then derived from the 2024 annual revenue and the annual number of articles published by each outlet. To account for price changes between 2000 and 2024 (+34.3% relative to 2000, +22% relative to 2010, and +16.2% relative to 2017), as well as the observed distribution of publications over the period, the average price of €11,507 per article was adjusted downward to €9,200.



APPENDIX 2: MAIN CNRS LABORATORIES AND PARTNERS INVOLVED IN CCUS RESEARCH

Laboratory acronyms	Joint supervision	CO ₂ capture and separation	CO ₂ transport	CO ₂ storage	CO ₂ utilisation	Institute	Laboratory name
BIP	AMU	X			X	INSB	Bioénergétique et ingénierie des protéines
CEMCA	UBO				X	INC	Chimie, Électrochimie moléculaire et chimie analytique
DCM	Univ Grenoble Alpes				X	INC	Département de Chimie Moléculaire
EM2C					X	INSIS	Laboratoire d'énergétique moléculaire et macroscopique, combustion
Georessources	Univ Lorraine	X		X	X	INSU	GeoRessources
GET	Univ Toulouse, IRD, CNES	X		X	X	INSU	Géosciences Environnement Toulouse
I2M	Univ Bordeaux	X		X	X	INSIS	Institut de mécanique et d'ingénierie
IC	Univ de Strasbourg	X				INC	Institut de Chimie de Strasbourg
IC2MP	Univ Poitiers				X	INC	Institut de Chimie des Milieux et Matériaux de Poitiers
ICCF	UCA, CHU Clermont			X		INC	Institut de Chimie de Clermont-Ferrand
ICGM	Univ Montpellier	X			X	INC	Institut Charles Gerhardt Montpellier
ICMPE	UPEC				X	INC	Institut de Chimie et des Matériaux Paris-Est
ICMUB	Univ Bourgogne			X	X	INC	Institut de Chimie Moléculaire de l'Université de Bourgogne
ICPEES	Univ Strasbourg			X		INC	Institut de Chimie et Procédés pour l'Énergie, l'Environnement et la Santé
IEM	Univ Montpellier				X	INC	Institut européen des membranes
IODE	Univ Rennes	X	X	X	X	INSHS	Institut de l'Ouest : Droit et Europe
IP	UCA				X	INSIS	Institut Pascal
IPCM	Sorbonne Université				X	INC	Institut Parisien de Chimie Moléculaire
IRCELYON	Lyon 1, Univ Lyon	X			X	INC	Institut de Recherches sur la Catalyse et l'Environnement de Lyon
ISTO	Univ Orléans, BRGM, OSUC			X		INSU	Institut des Sciences de la Terre d'Orléans
LCBM	CEA, Univ Grenoble Alpes				X	INC	Laboratoire de Chimie et Biologie des Métaux
LCC	INP, Univ Toulouse				X	INC	Laboratoire de chimie de coordination
LCM	IP Paris	X			X	INC	Laboratoire de Chimie Moléculaire
LCPB	College de France				X	INC	Laboratoire de Chimie des Processus Biologiques
LCS	UniCaen, ENSI CAen	X		X	X	INC	Laboratoire de catalyse et spectrochimie
LFCR	UPPA	X		X		INSIS	Laboratoire des Fluides Complexes et leurs Réservoirs
LGC	Univ Toulouse, Toulouse INP	X				INSIS	Laboratoire de génie chimique
LiPhy	Univ Grenoble Alpes	X				INP	Laboratoire interdisciplinaire de physique
LPP	IP Paris, Sorbonne U, Paris Saclay, PSL, Obs de Paris	X			X	INSIS	Laboratoire de physique des plasmas
LRGP	Univ Lorraine	X		(X)	X	INSIS	Laboratoire Réactions et Génie des Procédés
NIMBE	CEA, Univ Paris Saclay				X	INC	Nanosciences et innovation pour les matériaux, la biomédecine et l'énergie
RAPSODEE	IMT Mines Albi	X	X	X	X	INSIS	Centre de recherche d'Albi en génie des procédés des solides divisés, de l'énergie et de l'environnement
SyMMES	CEA, Univ Grenobles Alpes, INP				X	INC	Systèmes moléculaires et nano matériaux pour l'énergie et la santé
TBI	Inrae, INSA Toulouse	X			X	INSIS	Toulouse Biotechnology Institute, Bio & Chemical Engineering
TREE	UPPA			X		INSHS	Transitions énergétiques et environnementales
UCCS	Univ Lille, Centrale Lille, Univ Artois	X		X	X	INC	Unité de Catalyse et de Chimie du Solide

The list is based on responses to the 2023 and 2025 Energy surveys and includes only laboratories reporting more than 4 FTEs on the topic.

APPENDIX 3: THE 10 MOST HIGHLY CITED CNRS SCIENTIFIC PUBLICATIONS (SOURCE: WOS)

As a reminder, the “Highly Cited Papers” identified by Web of Science are articles published since 2015 that rank in the top 1% of the most cited articles published in the same year and in the same scientific field, here primarily chemistry.

1

869 CITATIONS

Visible-light-driven methane formation from CO₂ with a molecular iron catalyst (2017)
Rao, H; Chmidt, LCS; Bonin, J; Robert, M. Nature 548(7665), pp.74

France/Argentina

2

800 CITATIONS

Molecular electrocatalysts can mediate fast, selective CO₂ reduction in a flow cell (2019)
Ren, SX; Joulié, D; Salvatore, D; Torbensen, K; Wang, M; Robert, M; Berlinguette, CP. Science, 365(6451), pp.367

France/Canada

3

756 CITATIONS

Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions (2016)
Juerg, MS; Snaebjornsdottir, M; Sandra, O; Oelkers, EH et al. Science, 352(6291), pp.1312

France/United States/
United Kingdom/Iceland

4

552 CITATIONS

Photocatalytic CO₂ reduction (2023)
Fang, SY; Rahaman, M; Bharti, J; Reisner, E; Robert, M; Ozin, GA; Hu, YH. Nature Reviews Methodes Primers (3)1

France/United States/
United Kingdom

5

480 CITATIONS

Liquids with permanent porosity (2015)
Giri, N; Del Pópolo, MG; Melaugh, G; Greenaway, RL; Rätzke, K; Koschine, T; Pison, L; Gomes, MFC; Cooper, Al; James, SL. Nature 527(7577), pp.216

France/Argentina/Ireland/
United Kingdom/Germany/France

6	460 CITATIONS Substantial global carbon uptake by cement carbonation (2016) Xi, F; Davis, S; Ciais, P; Crawford-Brown, D <i>et al.</i> Nature Geoscience 9(12), pp.880	China/United States/ France
7	368 CITATIONS Fast, Ambient Temperature and Pressure Ionothermal Synthesis of Three-Dimensional Covalent Organic Frameworks (2018) Guan, XY; Ma, YC; Li, H; Yusran, Y; Xue, M; Fang, QR; Yan, YS; Valtchev, V; Qiu, SL., Journal of The American Chemical Society, 140(13) pp.4494-4498	China/United States/ France
8	335 CITATIONS Hydrolytically stable fluorinated metal-organic frameworks for energy-efficient dehydration (2017) Cadiou, A; Belmabkhout, Y; Adil, K; Bhatt, PM; Pillai, RS; Shkurenko, A; Martineau-Corcos, C; Maurin, G; Eddaoudi, M. Science, 356(6339) 731-735	France/Saudi Arabia
9	301 CITATIONS Negative emissions physically needed to keep global warming below 2 °C (2015) Gasser, T; Guivarch, C; Tachiiri, K; Jones, CD; Ciais, P. Nature Communications, 6:7958	France/Japan/ United Kingdom
10	230 CITATIONS Best practices for experiments and reporting in photocatalytic CO ₂ reduction (2023) Bonchio, M; Bonin, J; Ishitani, O; Lu, TB; Morikawa, T; Robert, M <i>et al.</i> Nature Catalyst 6(8) 657-665	France/Italy/Japan/ Germany/United Kingdom/ China/United States

APPENDIX 4: LIST OF INTERVIEWEES IN THIS STUDY

INTERVIEWS WITH SCIENTIFIC STAKEHOLDERS

INTERVIEWEES	POSITION
Fabrice Lemoine	Professor (University of Lorraine, LEMTA); coordinator of the PEPR SPLEEN
Antonio Pires Da Cruz	Programme Manager, IFPEN; coordinator of the PEPR SPLEEN
Vincent Artero	CEA Research Director; Director of the LCBM
Marc Robert	Professor (Sorbonne University, IPCM)
Thibault Cantat	CEA Research Director (NIMBE); currently at the ANR
Xavier Arnauld de Sartre	CNRS Research Director (ISTerre); coordinator of the PEPR “Subsurface: a common good”
Pascale Benezeth	CNRS Research Director (GET)
David Farruseng	CNRS Research Director (IRCELYON)
Sabine Rode	Professor (University of Lorraine, LRGP)

INTERVIEWS WITH OTHER STAKEHOLDERS

INTERVIEWEES	POSITION
Florent Guillou	Project Manager, IFPEN
Isaline Gravaud	Head of the CO ₂ Programme, BRGM
Basile Goussard	CTO, NetCarbon
Vincent Piepiora	CEO, Energo
Bernard Salha	Head of R&D and Technical Director, EDF
Jean-Luc Reboul	CTO CO ₂ & Energy, ArcelorMittal
Philipp Llewellyn	Advisor to the CO ₂ Techno Hub, TotalEnergies
Eric Bourdon	Deputy Managing Director, Vicat
Régis Réau	Former Scientific Director of R&D, Air Liquide
Florence Delprat-Jannaud	Chair of Club CO ₂ , IFPEN
Karima Benelhadj	Head of the Chemicals and Environment Sector, Bpifrance
Philippe Vercherin	Crédit Mutuel Impact
Hoang Bui	Coordinator for Low-Carbon Hydrogen and Industrial Decarbonisation, SGPI
Frédéric Branger	Head of the Carbon Markets and Industrial Decarbonisation Unit, DGEC
Solène Bouvier and Aude-Claire Houdon	ADEME
Ginette Vastel	Vice-President, France Nature Environnement



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