Position paper ANCRE

Carbon sinks

What role for research in accelerating their development in France?

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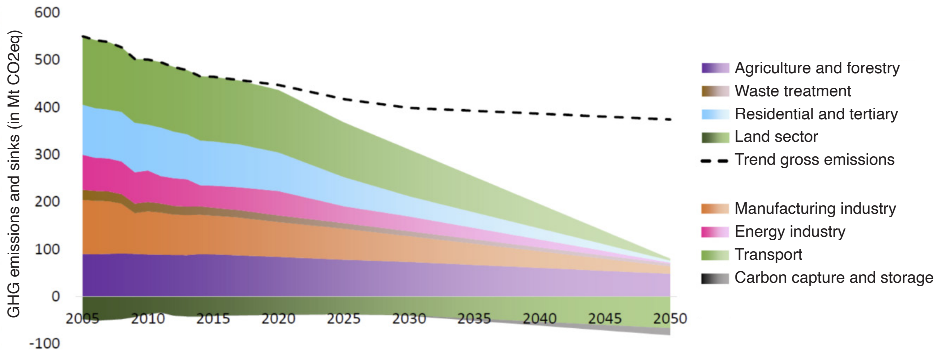
Introduction

In contribution to the national and EU objective of achieving carbon neutrality by 2050, a growing number of prospective exercises aimed at anticipating possible futures in terms of the deployment of solutions to achieve this target. On the basis of sectoral emission reduction trajectories, most of these studies use negative emissions (or carbon sinks) to offset fossil CO_2 emissions that would be too difficult to reduce in the next three decades.

Trajectory of greenhouse gas emissions and sinks in France between 2005 and 2050 in the AMS scenario (Source: SNBC, 2020).



The figure above illustrates a trajectory of emissions reductions and increases in GHG sinks to achieve carbon neutrality by 2050 in one of the National Low Carbon Strategy scenarios (AMS scenario). As in most of the scenarios aiming at this neutrality target from 2020, the use of carbon sinks is necessary. These sinks can be ensured by the implementation of various solutions from the land sector and/or form technologies of CO_2 capture and storage where CO_2 is emitted by industry or from atmospheric origin. At present, GHG sinks in France are mainly fed by carbon storage in terrestrial ecosystems such as biomass and agricultural, forest and wetland soils, in the form of organic matter. They are also fed by carbon storage in coastal ecosystems in the form of organic carbon and dissolved organic carbon.

In order to constitute sinks, this carbon storage must, over a given period of time, be greater than the release of carbon and increase over time. Increasing but also preserving carbon sinks and, in some cases, restoring them, are therefore priority issues. In order to increase these sinks and ensure the sustainability of storage, several levers can be envisaged. These include the specific management of these ecosystems, but also the development of dedicated technologies for capturing and sequestering CO_2 or carbon in dedicated tanks or long-lasting materials.

In the light of this transition, several questions arise as to the conditions for achieving these trajectories for the deployment of carbon sink solutions:

- What are the solutions for capturing atmospheric CO_2 and storing it sustainably?
- How can we guarantee the effectiveness of sustainable storage, regardless of their level of dependence on human activities and extreme natural events?
- How can we ensure that the current wells in French territories are at least preserved?
- What is the potential of French territories to develop new wells? What are the timeframes?
- What research actions should be implemented to reach these targets?

With this document, the ANCRE working group aims to shed light on different categories of solutions that can contribute to increasing carbon sinks at the national level.
Thanks to the analysis of the different issues and barriers associated with these solutions, recommendations for research and support actions are then defined to quantify their potential and accelerate their deployment. The following sections propose:

- Seven summary sheets corresponding to each of the selected carbon sink solutions.
- A selection of seven examples of recommendations for research and support actions, transversal to the different solutions, which appear to be among the most important to develop in the short term.

Worksheets by type of solutions

Six main categories of solutions contributing to the maintenance and development of carbon sinks have been dissingled out. Among them, three categories of solutions concern the natural capture of CO_2 in more or less anthropised environments, and three categories of so-called technological solutions that aim to accelerate natural processes and deploy new means of capture and storage. This document provides 7 descriptive worksheets to help understand the main issues.

Natural CO_2 capture solutions in more or less anthropised environments

Worksheet 1

Carbon storage in biomass and agricultural and forest soils

Worksheet 2

Carbon storage in biomass and soils in urban and anthropised environments

Worksheet 3

Carbon storage in aquatic environments and from rock weathering

Technological solutions for the capture and long term storage of atmospheric CO_2

Worksheet 4

Technological solutions for the capture of atmospheric CO_2 for geological storage

Worksheet 5

Storage of CO_2 in materials via mineralisation

Worksheet 5 bis

Biogenic CO_2 capture and storage in bio-based materials

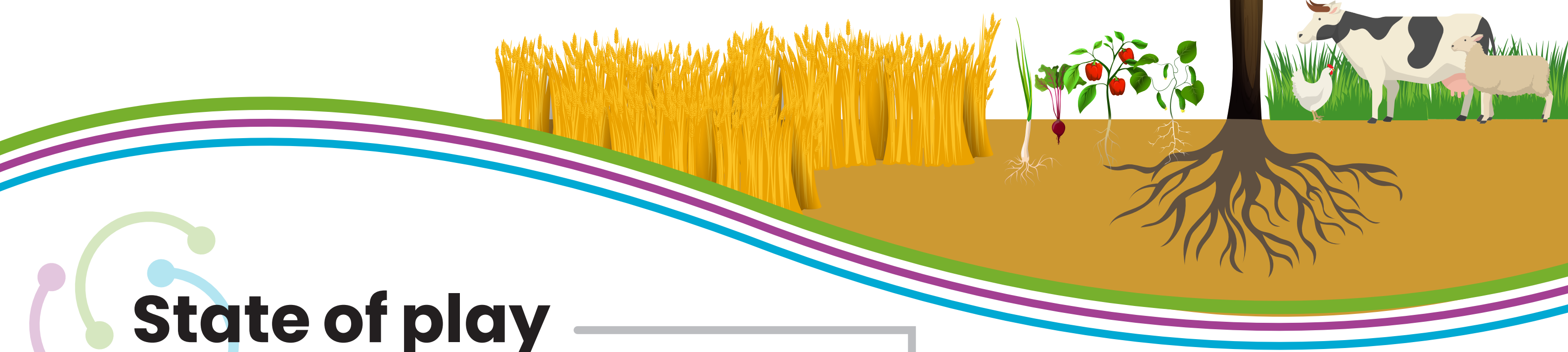
Worksheet 6

Technological solutions for recycled carbon capture, utilisation, and long-term storage

Each of the 7 worksheets is made up of 4 parts including :

- a summary description of the scope of application and the state of deployment of the solution in France,
- the various associated challenges,
- the current and potential barriers encountered,
- recommendations for research and support to accelerate its development.

Carbon storage in biomass and agricultural and forest soils



State of play

The natural mechanism of photosynthesis allows the sequestration of atmospheric CO_2 in the form of organic matter, in almost equal parts, between agricultural and forest biomass and soils. French terrestrial ecosystems already constitute a very significant carbon sink that EFESE estimates in Metropolitan France at nearly 20% of 2015 French emissions, i.e. approximately 90 Mt CO_2 eq/year [EFESE, 2019]. The vast majority of these sinks are in forest environments (more than 60 Mt in 2018 in mainland France according to ADEME, 2021). In the French Overseas Territories and in Guyana in particular, it is considered that these forests have reached their maximum carbon storage capacity and therefore their sink seems to have stopped (according to ADEME Guyane, 2016).

With regard to metropolitan soils in particular, the study conducted by INRAE in 2019 indicates that forest soils account for 38% of the total carbon stock, permanent grasslands 22% and field crops 26.5%. It is the latter which have the highest additional storage potential in the litter because of their current low carbon content and the size of their surfaces. On the already hand, for forest soils and permanent grasslands, which have a high carbon content, the challenge is to maintain their stock and preserve their surface area. The report highlights concrete actions to maintain and develop carbon storage in soils and the type of practices to achieve this, assuming no change in land use. The practices are potentially diverse (agroforestry, intermediate crops, hedges, extension of temporary grasslands, return of co-products to the soil, etc.) and they are accompanied by co-benefits in terms of water quality and biodiversity. However, all these practices must be considered in a given geographical and temporal context (soil conditions, stocks of origin, costs in line with existing crop rotation and existing opportunities). Through this study, a maximum additional storage potential of 30 Mt of CO_2 eq/year has been estimated for agriculture. However, there are many major risks to these carbon sinks due to, among other things, the reduction in forest area as a result of fires, pest attacks, drought and reductions in area through changes in land use. More work is therefore needed to improve understanding of the long-term effects of these practices and the effects of climate change on storage and sequestration.

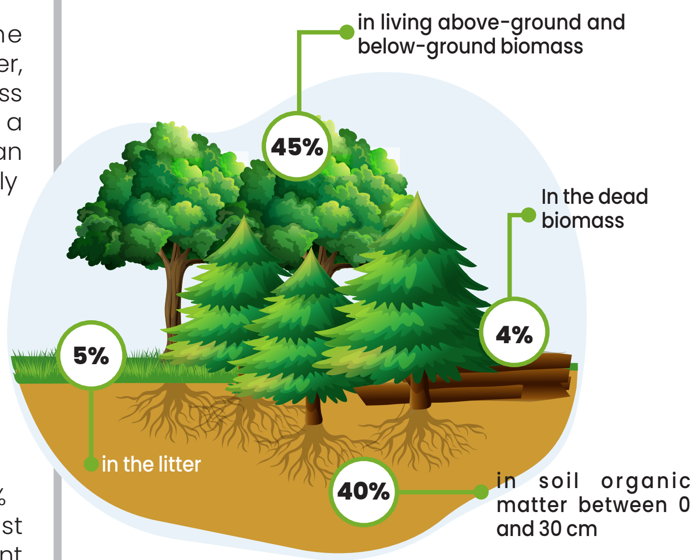


Figure 1 - Carbon storage in the forest
(ADEME, 2021)

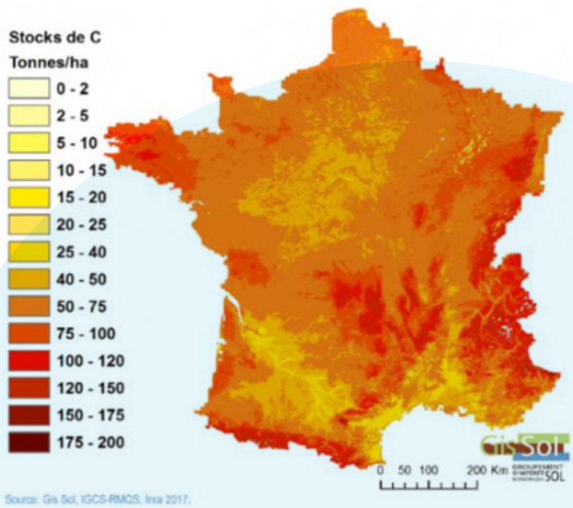
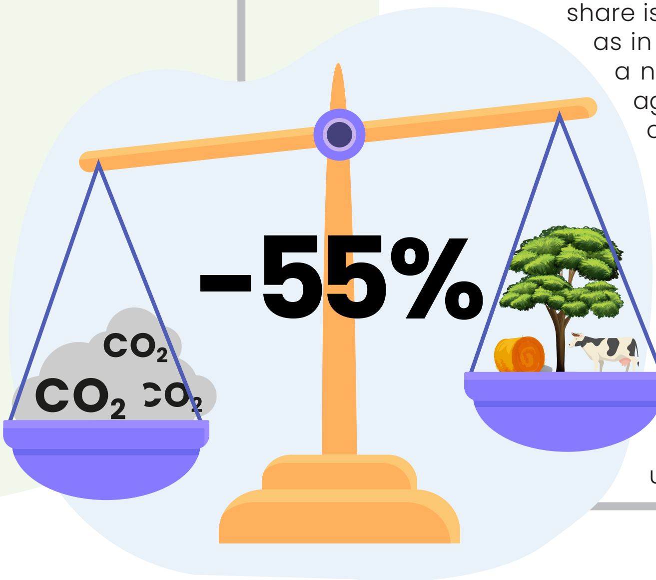


Figure 2 - Mapping carbon stocks in metropolitan soils (INRAE, 2019)

Challenges

At EU level, among the measures to accompany the latest proposed target of at least a 55% reduction in GHG emissions by 2030 are actions to preserve and expand the capacity of natural carbon sinks in each Member State, with binding targets from 2026. By 2035, the Union should strive to achieve climate neutrality in land use, forestry and agriculture [...] (Green Pact for Europe of 14 July 2021).

In addition, in its National Low Carbon Strategy (SNBC, 2020), France attributes an important role to natural carbon sinks for achieving carbon neutrality in 2050, which should be doubled to reach approximately 65 Mt CO eq2 /year in 2050, of which a growing share is in long-lived wood products (20 Mt, see sheet 5bis) as well as in agricultural areas (11 Mt). This scenario is accompanied by a number of measures such as increasing carbon storage in agricultural soils through changes in practices; the development of active and sustainable forest management, allowing both the adaptation of the forest to climate change and the preservation of carbone stocks in the forest ecosystem; the development of afforestation adapted to climate change and the reduction of land clearing.



France must therefore now acquire the means to consolidate existing data and knowledge in order to specify the real potential of these carbon sinks and to improve the monitoring of land use and the understanding of carbon dynamics within ecosystems. It also appears necessary to construct quantified scenarios of the evolution of these sinks under the impact of climate change. Locks

Barriers

LACK OF DATA
on the current evolution of carbon stocks and fluxes in ecosystems and the interactions between carbon, nitrogen and water,

LACK OF PROJECTION
on the dynamics of these developments under the impact of climate change,

LITTLE BACKGROUND
on the effects of changes in agricultural practices on long-term carbon storage,

LACK OF SCENARIOS
on projections under the impact of climate change,

NEED FOR TRACEABILITY
competition between agricultural and forestry land uses and artificial development (land reclamation vs.urbanisation),

LACK OF STUDIES AND INDICATORS
on assessing the environmental impacts of biomass harvesting,

LACK OF KNOWLEDGE
and regulations on the agronomic use of bioenergy co-products (digestates, biochar, etc.),

COMPARTMENTALISATION OF SECTORS
agri-food and energy, lack of systemic vision,

LACK OF PUBLIC POLICY
in the long term and lack of coherence between agricultural, food and energy policies,

Actions

Research recommendations

Behaviour of media and products:

- **Propose technological solutions** for in-situ biogeochemical analyse (biosensors, miniaturised geochemical and geophysical sensors, smart samplers).
- **Maintain databases** and samples of French soils, including the diversity of the macrofauna and microflora of the soil.
- **Build databases** on material transfer processes and establish behaviour laws to assess the consequences of these transfers (quantify the closing of C, N, P cycles).
- **Analyse the sensitivity** of ecosystems to the export of small wood and the return of ash to the soil (Sensitivity indicators for major mineral elements and overall combination - Field diagnostics).
- **Develop multi-criteria approaches** to the duality of biomass removal addressed on all elements: physical, chemical and biological, develop multiscale predictive models of the evolution of sustainability indicators.
- **Understanding the relation between the structure** of biochars and digestates from methanisation and their properties when returned to the soil.
- **Develop scenarios** for sustainable biomass harvesting at the levels of territories under climate change impact.

Identification of practices

- **In terms of silvicultural** practices, develop biophysical and economic approaches to identify practices for sustainable forest management (conversion of coppice to high forest, reasoning out soil preparation, avoiding clear-cutting with soil degradation, not harvesting the whole tree), and transfer these stocking practices to professionals.
- **Develop strategies for optimising climate** change mitigation in the choice of stand rotation length at the scale of territories, propose new stands with species resistant to biotic and abiotic stresses (rather than considering only one economic criterion).
- **Conducting trials on forest** (and agroforestry) plots to intensify biomass growth and soil carbon storage, carrying out complete balances of the biogeochemical cycle of the plots over a long period of time and then integrating the entire (multiproduct) wood value chain.
- **In terms of agricultural practices:** broaden the species of intermediate crops and refine the practices of insertion in rotations; deepen the trials of spreading digestates and biochars, characterise the carbon that can be stored and feed the soil/microorganism/plant models.
- **Couple pyrolysis** and methanisation for the agronomic quality of the digestate and favour its return to the soil.

Implementing recommendations

- Need to centralise, record and appraise FAIR data from experiments with new practices and environmental behaviour,
- Deploy or maintain the national infrastructure for long-term monitoring of C, N, P cycles.
- Deploy projects that can benefit from a low-carbon label with generation of carbon sinks in agricultural and forestry environments.
- Identify the full range of ecosystem services from new practices.
- Strengthen public agricultural and forestry policies at national and territorial levels that promote sustainable agricultural and forestry practices to increase carbon storage.
- Identify and reforest degraded land.
- Enable the resilience and adaptation of forest stands to the effects of climate change so as to ensure the preservation of their different ecological functions in order to carry out mitigation action.

Worksheet 2

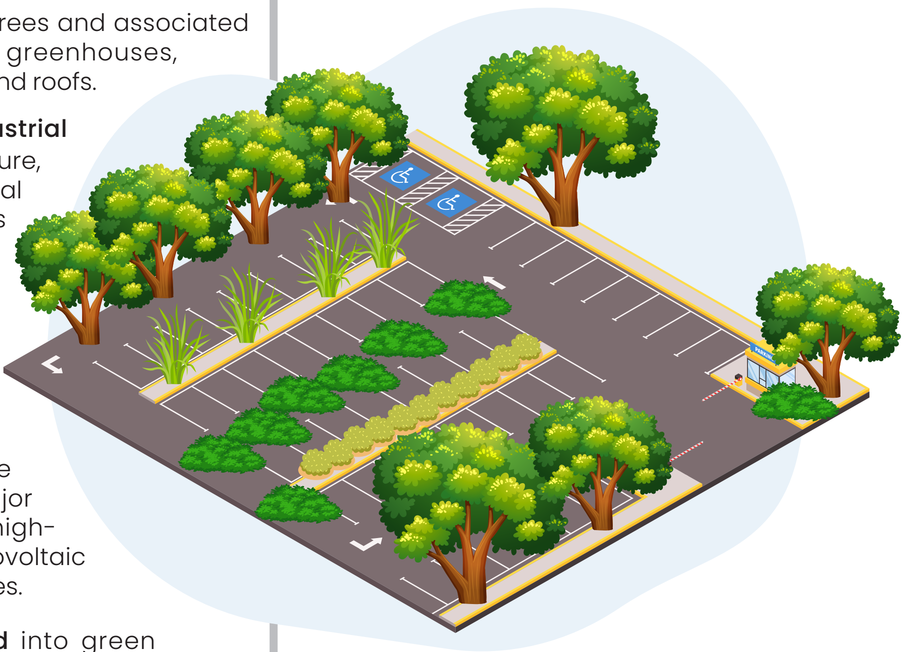
Carbon storage in biomass and soils in urban and anthropised environments

State of play

Urban areas and, more generally, highly anthropised areas cover a wide range of environments in which the capture and storage of CO_2 by biomass can constitute carbon sinks. In particular, the following can be distinguished:

Green Urban spaces: parks, gardens, line trees and associated soils and substrates; urban agriculture, greenhouses, especially shared gardens; green facades and roofs.

Recently or decades ago **abandoned industrial wastelands**, more or less reinvested by nature, or wastelands in the making (e.g. commercial areas). These include: industrial wastelands that have not been converted into housing (former industrial sites, railway wastelands); military wastelands; former mining sites; and commercial wastelands.



The areas disturbed by civil engineering operations around transport infrastructures, and which have been grassed over. Examples include peri-urban areas in the immediate vicinity and on railway embankments, major roads, airport areas, areas occupied by high-voltage lines, solar panels areas (e.g. photovoltaic farms) that do not allow agricultural practices.

Urbanised areas that can be converted into green spaces, such as car-free areas in cities where cars are to be removed. Abandoned highly anthropised environments are subject to the establishment of vegetation (spontaneous or not), which can evolve into a cultural, or grassland, or forest ecosystem, providing a wide range of ecosystem services, including carbon storage. They can result in the generation of carbon sinks, provided that appropriate practices are developed and applied. For example, brownfields that are reclaimed for landscaping, biomass production, heat island mitigation or renaturation purposes, or operations to restore soil functions can lead to additional carbon storage. Soil construction technologies exist for this purpose and already have enabled the renaturation of former industrial and mining sites.

Challenges

Old industrial sites may contain very old carbon (from mining and oil extraction), which can be found at depths of more than a metre. These situations show the existence of a storage potential that can be increased through appropriate management strategies. However, there is a lack of information on the surfaces concerned, as well as on the current practices that could be developed for storage on surfaces such as the edges of roads, railways, airports and also highly anthropised recreational areas such as golf courses. The land pressure on these areas also differs greatly depending on their location in relation to urban centres (e.g. brownfield in urban areas vs. isolated brownfield in rural areas) and therefore their potential for carbon storage varies greatly from one point to another. Urban management strategies are also a factor in assessing carbon storage potential (e.g. greening policy).

The conversion of urban wastelands into green spaces could be applied to a larger number of sites to be greened. They could also be optimised with a view to increasing the quantity and duration of storage, while ensuring their primary function. Some of these areas are also highly sought after (e.g. brownfield sites) for photovoltaic development, leading to trade-offs to ensure the widest range of ecosystem services.

As regards municipal parks/gardens, railways and urban agricultural plots, data enabling the surfaces concerned to be evaluated are not readily available on the scale of the entire metropolitan territory. Evaluations show a total additional storage potential for industrial wastelands of between 3.5 and 4.7 Mt of CO_2 equivalent by 2050 (with a 25% share of mobilised surfaces in 2050, with a total of 530 000 to 705 000 hectares). For airport areas, the total additional storage potential is around 0.65 Mt CO_2 eq. by 2050 with the implementation of renaturation, considering no increase in surface area. For green facades and green roofs, the potential is estimated at 0.13 Mt CO_2 eq. by 2050, considering no increase in surface area. For roads, the potential is of the order of kiloton of CO_2 eq.

In summary, while the potential exists, it is not really known nor quantified. Technologies are available but could be optimised with a view to increasing storage while ensuring the provision of essential ecosystem services such as biodiversity.

The challenge is to determine the existing and potential surfaces in urban and antropised environments that allow for the most effective carbon storage (in terms of quantity and durability) by integrating carbon storage into the decision-making process for the use of these surfaces in order to meet the objective of carbon neutrality in 2050, as this storage possibilities have not yet been demonstrated or used.

Barriers

LACK OR DIFFICULTY OF REALISTIC EVALUATIONS
of the areas concerned and the potential carbon storage in relation to the uses.

DYNAMICS OF THE PROVISION OF SURFACES
(e.g. commercial wasteland, temporary renaturation of wasteland before new use).

LAND USE COMPETITION
and complementarities with urbanisation/housing projects, renaturation, energy production.

SIMULTANEOUS CONSIDERATION
Of the coupling of carbon storage and the impact on biodiversity, particularly in sites that are not subject to building development.

LACK OF INFORMATION TO STAKEHOLDERS

- of transport infrastructure management and technological developments to adopt storage practices (roadsides, railways, airport areas, etc.).
- of building contractors, and technological developments allowing storage, especially when excavating soil for building construction.

Actions

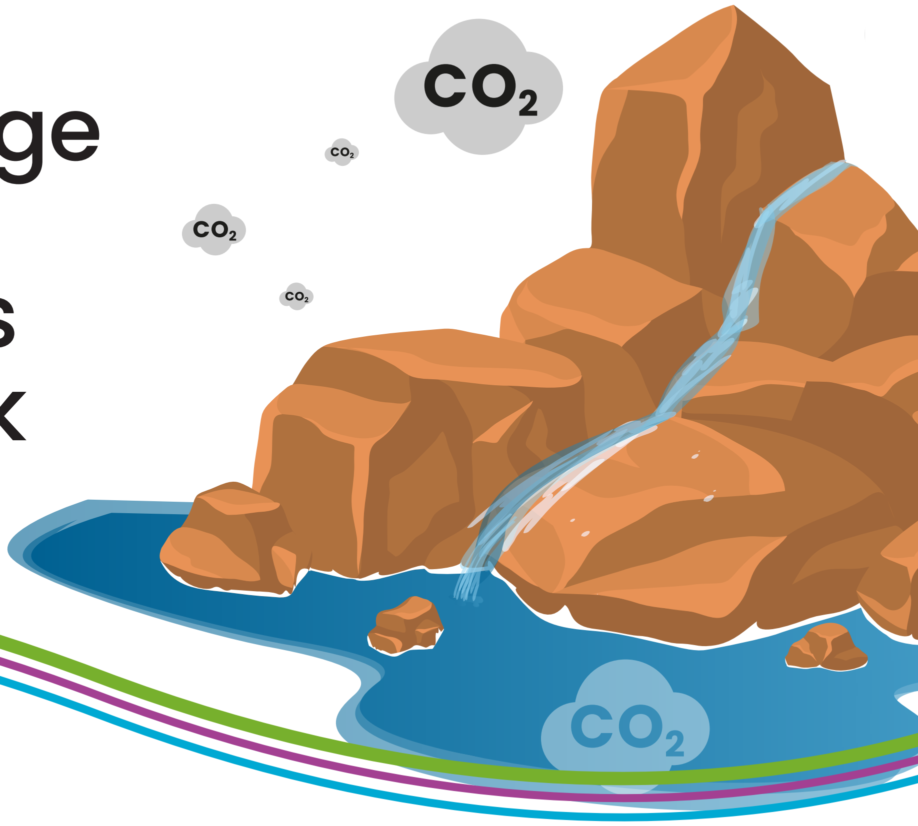
Research recommendations

- Need to set up observatories or territorial statistical monitoring to quantify surface areas; mobilisation of spatial planning actors (e.g. Public Landholding Establishments).
- Need to set up observatories and systems to evaluate practices in order to quantify their impact on the evolution of carbon storage (for all potential storage areas - construction, cemeteries, landfills, etc.): this is a key issue for the European Union.) :
  (i) inventory of practices,
  (ii) assessment of the impact in terms of storage,
  (iii) implement the identified stocking practices to optimise these practices and/or their deployment.
- Carrying out emission balances vs. storage in parks, urban agriculture areas and shared gardens (focus on vegetated areas).
- Build functional soils capable of providing a wide range of ecosystem services (e.g. biodiversity, carbon storage, hydrology, oxygen production) pollution) :
  (i) Identify a few pilot sites to make comprehensive radiation balance measurements,
  (ii) monitoring cultivation practices in shared gardens or park maintenance,
  (iii) make a comparison between the urban and agricultural contexts in terms of practices, impact on carbon and biodiversity and their evolution.

Implementing recommendations

- Encourage the development of parks, gardens and forests in urban areas, green roofs and facades.
- Promote revegetation of brownfields and renaturation (biodiversity) by optimising carbon storage.
- Develop new storage strategies and practices during remediation of degraded and polluted sites.
- Implement tools to raise awareness among land-use planning actors of the need to change practices to increase carbon storage.
- Promote a better transfer of knowledge and innovative technologies concerning carbon storage to land-use planning actors (communication, exchanges...).
- Develop public policies that encourage (regulation, taxation, remuneration) the storage of carbon in these areas and preserve them over long periods.

Carbon storage in aquatic environments and from rock weathering



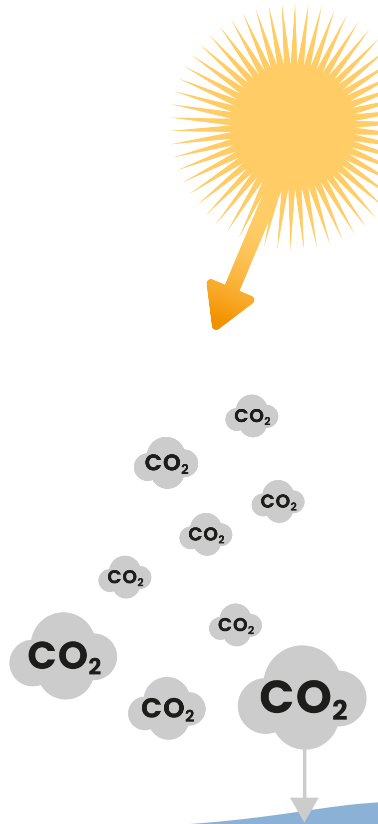
State of play

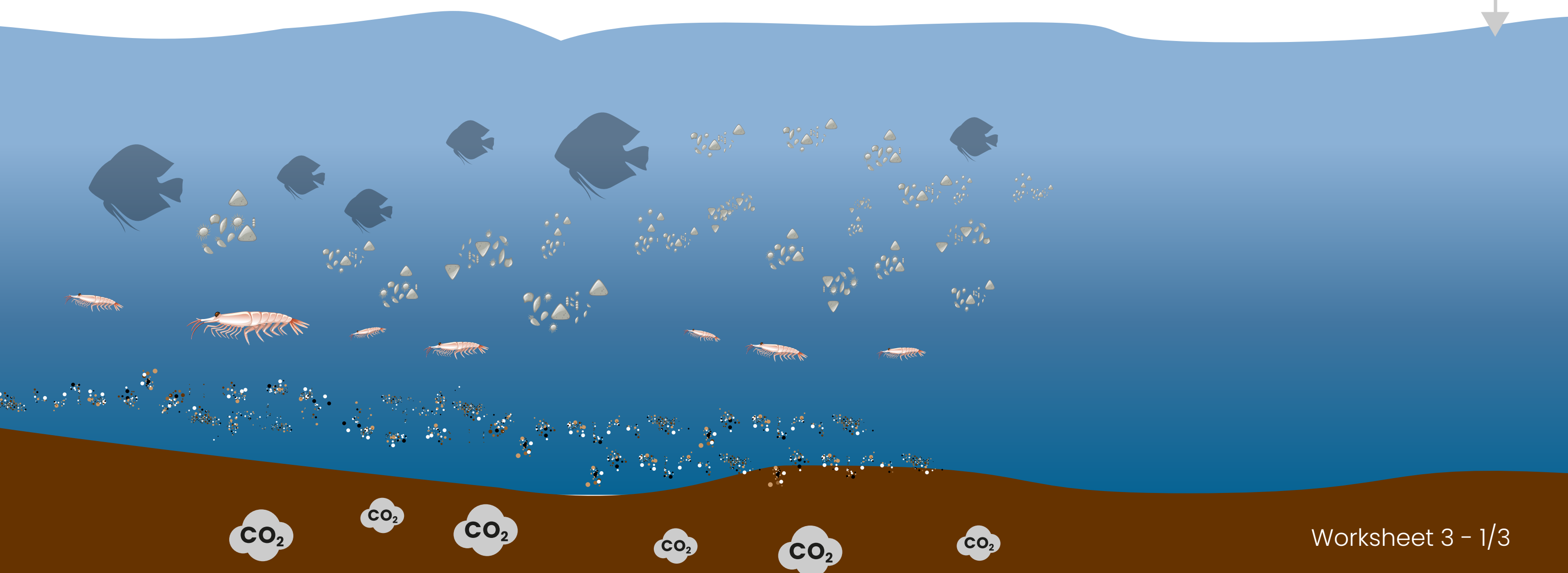
The carbon cycle, that integrates carbon dioxide (CO_2), refers to carbon fluxes within the different Earth's surficial reservoirs, and the biogeochemical processes, and physical exchanges that control them. It defines the stocks and exchanges over time scales ranging from decades to millions of years.

For metropolitan France and the French overseas territories, we made a inventory of the mechanisms linked to the net transfer of CO_2 from the atmosphere to aquatic environments, consisting of carbon sinks on time scales of more than a hundred years. We also examined the biogeochemical processes responsible for these transfers:

- Burial of continental and coastal organic matter (OM) during its transfer from the continent to the ocean;
- In environments characterized by high productivity and rapid burial such as deltas, mudflats, seagrass beds, mangroves, and estuaries;
- Alteration of silicate and carbonate rocks by carbonic acid;
- Oceanic carbon pump and storage in intermediate water masses via physical, chemical and biological processes.

In this review, we also explored the existing national research infrastructures capable of monitoring these carbon flows.





Challenges

The challenges we have identified are essential to establish the potential for CO_2 sequestration for the entire territory of France:

- Quantify the fluxes of atmospheric CO_2 trapped via the various biogeochemical processes occurring in continental (rocks, rivers and lakes), coastal (marshes, mangroves, deltas, seagrass beds) and oceanic environments;
- Quantify methane emissions from organic carbon storage in continental and coastal environments;
- Determine the sensitivity of sink/source environments to climatic and anthropogenic pressures;
- Deliberate on the definition of ocean storage in the French Exclusive Economic Zone (EEZ) in the context of international policy on CO_2
- Pursue mapping of the different sources and sink areas at the national level with the aim to achieve a sustainable management of the national carbon balance.

Barriers

The fluxes of CO_2 are often poorly constrained and in many cases even unknown. The factors affecting the intensity of these fluxes are even less well known, likewise their dependence on variations in climate and environmental parameters. Consequently, the total balance and future evolution of the CO_2 sequestration potential on the French territory remains elusive. To improve the carbon budget estimate, it is essential to pursue the study of the complexity of natural systems, i.e. the large variety of biogeochemical processes, their interdependence and temporal variability.

Continental and coastal areas:

POORLY CONSTRAINED AND UNDERSTOOD DYNAMICS OF THE ORGANIC MATERIAL:

mechanisms leading to burial and recycling (respiration and methanogenesis);

RESTRICTED KNOWLEDGE OF THE SPATIAL EXTENT OF SOURCE/SINK OF INTEREST

Necessity to map the total national area of rock weathering zones, lakes and retaining dams, coastal blue carbon areas with high storage potential and variability. This would improve the assessment of fluxes and stocks of carbon potentially modified by anthropogenic activities (coastal developments, port activity, dredging/trawling, dewatering for agriculture, aquaculture, etc.) or climate changes.

UNDERSTANDING THE EVOLUTION OF PROCESS DYNAMICS

carbon storage/release in relation to climate and environmental changes (temperature, extreme events, nutrient and carbon transfers, etc.).

The open ocean:

PHYSICO-CHEMICAL MECHANISMS

Well known but poorly quantified for carbon transfer to intermediate waters, with uncertainty on the biological pump and its evolution in response to climate change;

REDUCE UNCERTAINTIES

of the residence times of stored carbon before its release to the atmosphere.

Actions

We have identified the actions we believe important to remove the identified barriers and achieve the aforementioned challenges:

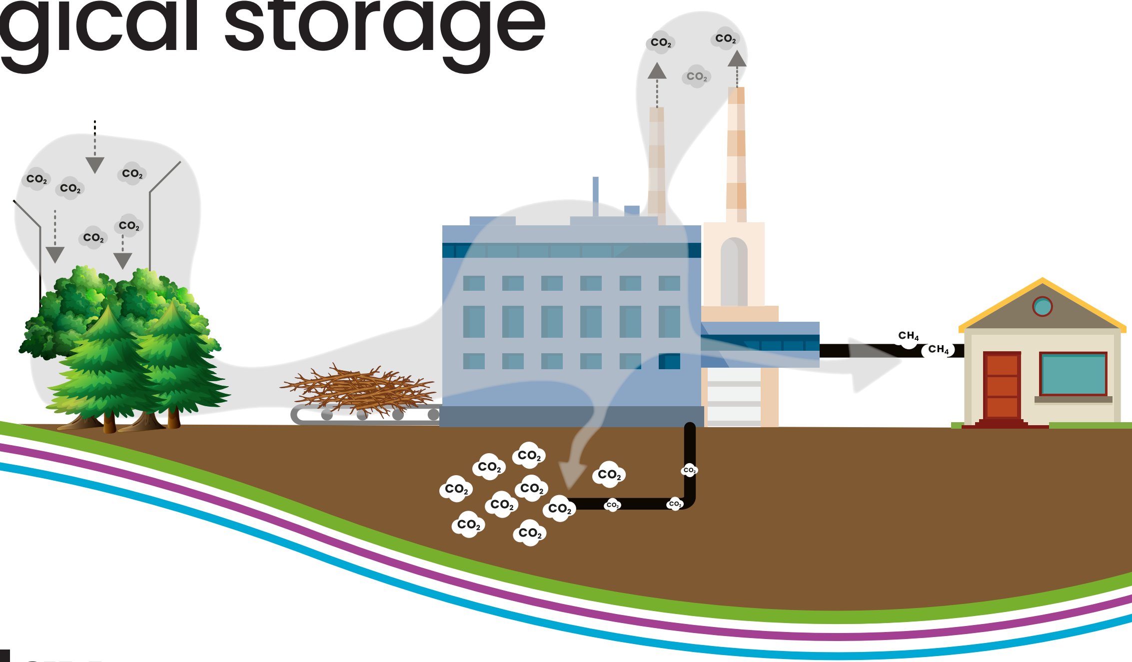
- Strengthen carbon observation systems in continental aquatic environments and coastal domains to take into account the complexity of the investigated systems at different spatial and temporal scales, and thus increase the volume of data available to facilitate the development of forecasting models, and even digital twins. This implies increasing the number of analytical techniques, and standardising and optimising measurement and sampling procedures. A national policy to support and maintain the existing observatories and to create new ones is essential. This also implies a scientific policy for data management: archiving, sharing, dissemination use and valorisation.

- Further investigate the biogeochemical processes related to sinks and sources of CO_2 by reservoirs and determine their time constants. Calculate net carbon balances by considering both CO_2 and CH4. This enhance the existing modeling and simulation tools use to infer the response of carbon sources and sinks undergoing to future anthropogenic and climate changes.

- Pursue research assessing the potential for CO_2 sequestration through actions that aims at protecting, preserving and restoring key carbon sink ecosystems.

- Launch discussions on how to consider ocean storage within the French EEZ in the international political context of greenhouse gas emissions, keeping in mind that storage is not permanent and moves from one EEZ to another.

Technological solutions for capturing atmospheric CO_2 for geological storage



State of play

CO_2 capture and storage technologies2 not only reduce CO_2 emissions , but also reduce CO_2 in the atmosphere (i.e. achieve negative emissions) through:

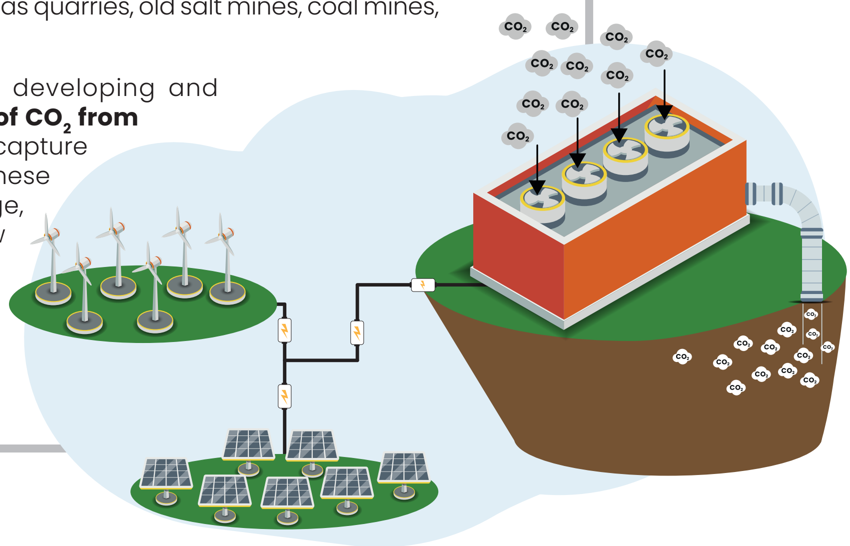
- Bioenergy with Carbon Capture and Storage (BECCS) where CO_2, emitted by a combustion process using biomass as fuel or biomass-fuelled industrial processes, is captured and CO_2 is stored underground;

- Direct air capture (DAC), which consists of directly capturing CO_2 already present in the atmosphere and, ultimately, storing it permanently underground.

Bioenergy with CO_2 capture and storage (BECCS) is the most mature of the technologies for removing carbon from the atmosphere, as both bioenergy and CCS have been proven separately on a commercial scale. The principle is the capture and storage of biogenic CO_2 emitted by biomass combustion or bio-mass-fuelled industrial processes. Several installations are in operation around the world, most of them associated with fermentation for ethanol production.

An alternative to BECCS is the **recovery of solid carbon in the form of biochar** co-produced by the biomass pyrolysis process for the production of energy (heat, electricity, fuel) and chemical compounds (see e.g. Lambiotte in Prémery). Biochar is a biogenic carbohydrate concentrate that can be spread on agricultural or forestry soils (see sheet n°1) or stored in geological cavities such as quarries, old salt mines, coal mines, etc.

In addition, several companies are developing and marketing **direct capture processes of CO_2 from the atmosphere,** most of them using capture processes based on solid sorbents. These installations are still at the pilot stage, the most important can capture a few hundred to 4,000 tonnes of CO_2 /year. The advantage of direct CO_2 capture lies in the possibility of installing the capture system close to the storage area and/or to abundant and cheap decarbonised energy production.



Challenges

The challenges for bioenergy with CO_2 capture and storage include:

1 - the adaptation of capture technologies to the different concentration levels of biogenic CO_2 from bioenergy units;
2 - the scaling up of certain biomass conversion technologies not yet demonstrated on a commercial scale (hydrothermal conversion, biofuels from microalgae, etc.) ;
3 - the technical and economic feasibility of the entire BECCS system.

These different challenges will have to be accompanied by the control of the different carbon flows throughout the life cycle of the system so as to ensure a negative emissions balance.

The main challenge for direct air capture is to reduce the energy penalty of the process and its implementation cost, as the concentration of CO_2 in air (0.04%) is about 300 times lower than in flue gas.

Barriers

Among the challenges to be addressed as a matter of priority are, for bioenergy with carbon or CO_2 capture and storage :

STRUCTURING THE SUPPLY
of biomass resources in order to be able to increase capacity,

DEVELOPMENT OF FACILITIES
of flexible combustion systems adapted to the variability of biomass and to the heat requirements on site

THE DEVELOPMENT OF CO_2 CAPTURE PROCESSES
adapted to the constraints of the emissions in terms of composition and flow of the flue gases

THE INTEGRATION OF THE SEPARATION OF CO_2
for gasification and pyrolysis processes.

For direct air collection :

SCALING UP
and integrating the impact on energy resources and materials needed,

PROCESS INTENSIFICATION,
and energy optimisation and the availability of decarbonised energy sources,

MEDIA DEVELOPMENT
for CO_2 separation system with low environmental impact,

GEOGRAPHICAL LOCATION
of capture sites according to carbon regulations and the availability of renewable energies.

The principle of negative emissions requires long-term storage of atmospheric CO_2 in various forms (gas in underground reservoirs, solid in surface soils or in the form of materials, etc.). The challenges of storing CO_2 in geological formations are the same as those of CCS:

SOCIETAL PERCEPTION
for use of the subsoil to store CO_2 ,

THE AVAILABILITY OF STORAGE FACILITIES
in a timeframe compatible with the CO_2 injection needs of projects under development

THE DEVELOPMENT OF ASSESSMENT METHODS
of environmental impacts, risk prevention and remediation, and long-term monitoring technologies.

The challenges for the long-term storage of solid carbon in biochar (from biomass pyrolysis) in biomines are the study of the mechanical and chemical stability of the biochar, the environmental issues (leaching of compounds present in the biochar by water), and storage engineering (optimising the yield in terms of mass of densified carbon in the biochar per unit of available volume).

The barriers associated with storage in agricultural and forest soils are covered in Fact Sheet 1, and the barriers associated with storage in materials are covered in Fact Sheet 5Les verrous associés au stockage dans les sols agricoles et forestiers font l'objet de la Worksheet n°1, les verrous associés au stockage dans les matériaux font l'objet de la Worksheet n°5.

Actions

Research recommendations

Strengthe research and innovate

- Improve CO_2 capture and purification processes for the thermal and biochemical conversion of biomass and waste, including **adaptability to biomass variability.** In this sense, it is necessary to (i) consolidate and analyse databases characterising the properties of biomass (and combustion flue gases) and (ii) identify components or molecules likely to present a risk for known storage sites.
- **Reduce the energy penalty** of the process chain by improving the energy integration of atmospheric CO_2 capture processes in particular, as well as by reasoning the energy needs by valorising fatal or low-carbon heat when appropriate.
- Investigate the development of **modular capture** processes to enable cost reduction and CO_2 recovery from small installations
- Study the s**torage of biochars** in underground cavities (creation of biomines) on different interdisciplinary aspects: (i) storage engineering (optimising the density of carbon stored per unit of apparent volume), (ii) socio-economic interests (potential conflicts of use/conflict of uses at the country or territorial level), (iii) environmental impacts (stability of the carbon, study of gaseous and liquid emissions).

Identify and quantify suitable storage capacity

- Continue the exploration, selection and characterisation of **storage sites** (deep geological reservoirs, old mines/quarries, etc.) on French territory (mainland France, French overseas departments and territories; onshore and offshore) as well as the availability of cross-border storage capacities.

Developing demonstration projects

- Validate the **performance of** existing **bioenergy technologies** (biomass plants, biofuel units) with a view to their connection to a CCS system; but also demonstrate innovative BECCS systems on new advanced bioenergy technologies (biojet, biomethane, multi-product biorefineries, etc.).
- **Optimise the logistical** solutions for the various flows (CO_2 , biomass): (i) integrate the existing transport networks in France and cross-border networks (gas pipeline, oil pipeline, sea/river routes, etc.) with regard to the sites of emissions, storage and use; (ii) define the sizing requirements of the transport networks with regard to the CO_2 flows and their seasonality.
- Testing the management of **CO_2 flows** (capture and transport) **on a small scale** (in locations potentially close to the biomass but far from storage locations).
- Develop **integrated direct air capture demonstrators** adapted to local conditions (access to decarbonised energy, access to a storage site or a CO_2 conversion site.)

Implementing recommendations

Develop impact analysis methods

- Develop methods of multi-criteria environmental analysis (in particular Life Cycle Analysis) based on mass balance (including carbon) and energy balances (from the demonstrators) allowing (i) the optimisation of processes (from soil to sequestered carbon, including all products); (ii) anticipate conflicts of use and potential impacts on the environment, land use and biodiversity; (iii) to extrapolate a large-scale deployment on the national territory.

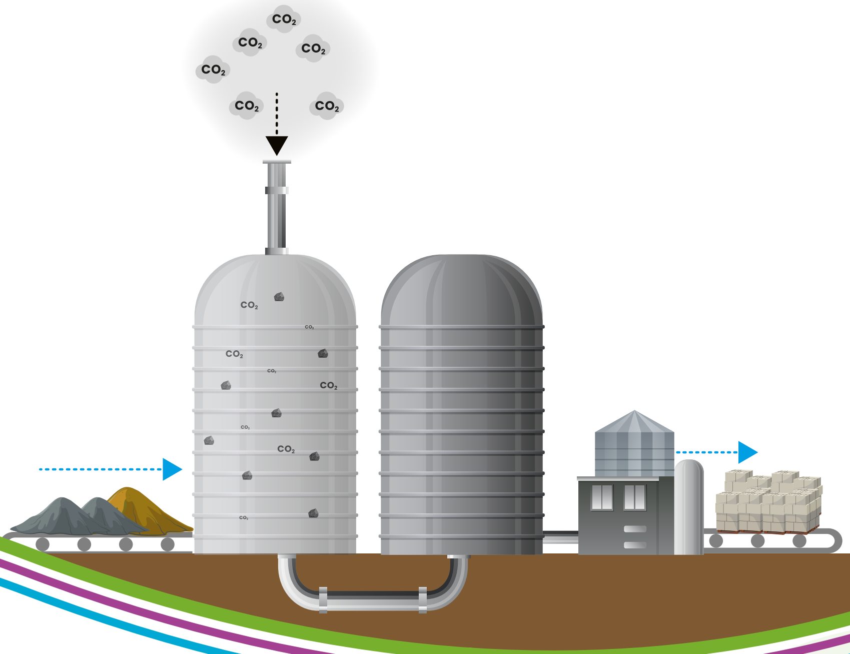
Develop engagement strategies

- Deploy consultation and co-construction actions by civil society stakeholders on the different pathways and projects, particularly with a view to communicating and informing on the principle and risks of storage.

Support the launch of first of a kind industry

- that will help launch the industry, reduce risks and gain skills.

Storage of CO_2 in materials via mineralisation



State of play

Mineralisation is a way of storing CO_2 in materials. It consists in accelerating the natural carbonation process known for its role in climate regulation using CO_2 from bioenergy, atmospheric capture or industrial gases. The cations (Ca, Fe, Mg) in the materials combine with CO_2 in the presence of water to form stable carbonates. Mineralisation occurs in ex-situ reactors which allow for fast kinetics and high yield. This CO_2 utilisation pathway can produce useful added-value materials from natural minerals, mine tailings or waste. This field is currently led by the USA, China, Canada, South Korea, Australia and the UK. It is also rapidly expanding with companies such as Carbon8, Carboncure, Solidia Technologies or MCi. A panoramic analysis reveals a high maturity of mineralisation for Calcium-rich feedstocks, in accord with the building materials sector.

				Calcium Feedtocks		Magenisum feedstocks	
				Ores (e.g. wollastonite)	Wastes (e.g. phosphogypse, BOF slag, deconstruction wastes)	Serpentinized ores (e.g. lizardite)	Not Serpentinized ores and wastes(e.g. olivine, nickel slags)
Solution	**Target**	**Products**	**Carbon impact**	Intermediate products : Ca^{2+} , $Ca(OH)_2$		Intermediate products : Mg^{2+} , $Mg(OH)_2$	
EX-SITU	Low carbon building materials	aggregates	Carbon sink				
		Supplementary cementitious materials	Carbon sink				
		Concrete blocks	Carbon sink				
		Ready-mix concrete	Carbon sink				
		Precipitated Ca/Mg carbonate	Carbon sink				
		Hydraulic binders (cement)	Avoided C				
	Other	Co-recovery of metals	Carbon sink				
		Co-production de H_2	Carbon sink				
IN-SITU	Storage		Carbon sink				

High maturity / commercial developments — Significant research and development — Largely unexplored

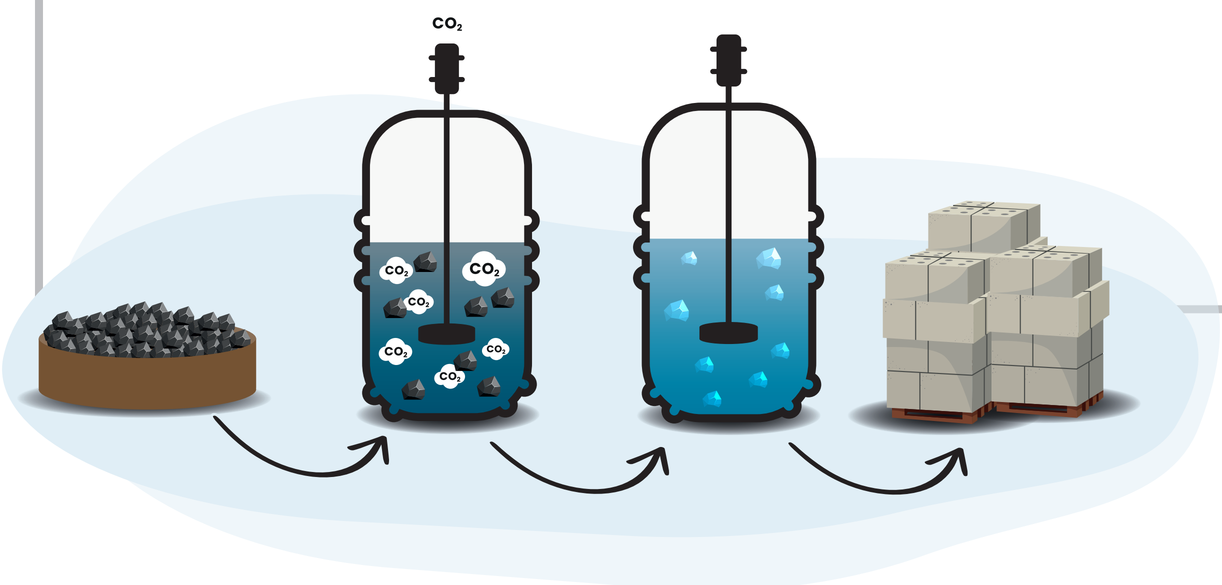
TotalEnergies, LafargeHolcim, Vicat, Air Liquide, Arcelor Mittal, Imerys, EDF, Eramet, Solvay and Veolia are active French companies in this area. The research side is led by CNRS, CEA, BRGM, CSTB, University Gustave Eiffel, University of Toulouse (LGC), University of Lyon (ICBMS), University of Paris and Université de Lorraine. The development of mineralisation in France is mainly at the R&D level for the production of valuable materials from industrial waste, with projects such as CARBOVAL , FASTCARB , VITAMINE and VALORCO . The coupling between mineralisation and metal extraction (MeCaWaRe Company), the production of H2 or the spreading of finely ground olivine for the capture of atmospheric CO_2 are among the most recent avenues of research and development.

1/ CARBOVAL (Mineralisation of waste from the mining industry) led by the University of Toulouse
2/ FASTCARB (Mineralisation of recycled concrete) led by the UGE and 22 partners
3/ VITAMINE (Mineralisation of CVE waste) supported by EDF
4/ VALORCO (Valorisation of CO_2 in the steel industry) supported by ArcelorMittal

Challenges

Achieving carbon neutrality in 2050 requires the development and deployment of CO_2 mineralisation technological solutions adapted to the French context, at the confluence of carbonatable material feedstocks, CO_2 emitters and markets. CO_2 sourcing is one critical issue for the development of mineralisation. It raises questions in terms of quantity, quality, availability, and economic value, during and after the transition period leading to the fully decarbonised energy mix foreseen by the French National Low Carbon Strategy (SNBC). CO_2 mineralisation using industrial by-products mainly concerns deconstruction waste (concrete, gypsum), ash and combustion products from coal or oil, incineration products (bottom and fly ash), mine tailings, and slags from metal manufacturing industries. It is estimated that the mineralisation of the approximately 2 billion tonnes of alkaline residues produced annually worldwide could (directly or through avoidance) reduce anthropogenic CO_2 emissions by 12.5% (Pan, SY et al. 2020). On the basis of 2019, it is estimated that the French deposit of carbonatable wastes could have made it possible to store approximately 6 Mt of CO_2. The carbonatable feedstock is likely to change over time. Despite the anticipated disappearance of certain wastes by 2050, such as ash and slag heap residues, new manufacturing processes that integrate CO_2 mineralisation could increase the carbonatable materials feedstock beyond 20 Mt of storable CO_2. This estimate is strongly associated with the construction sector, which has the capacity to turn cements/concretes into very large carbon sinks for CO_2 storage. The question of the availability of biogenic CO_2, i.e. not derived from fossil energy sources, is a point of vigilance.

5/ Expert estimates based on available carbonatable wastes (compilation of waste fluxes from various pathways in France, including French overseas territories).



Barriers

The development and deployment of CO_2 mineralisation processes in France (6 to 20 Mt of CO_2 equivalent) is based on access to and synergy between:

SUPPLY OF NON FOSSIL CO_2
constant over time, near carbonatable material feedstocks, with a high CO_2 content without penalising elements,

CARBONATABLE MATERIALS' FEEDSTOCKS
in sufficient and consistent quantity near CO_2 sources,

TARGET MARKETS FOR CARBONATED PRODUCTS
(e.g. building materials, precipitated calcium carbonate, flame retardants, mineral fillers, 3D printing).

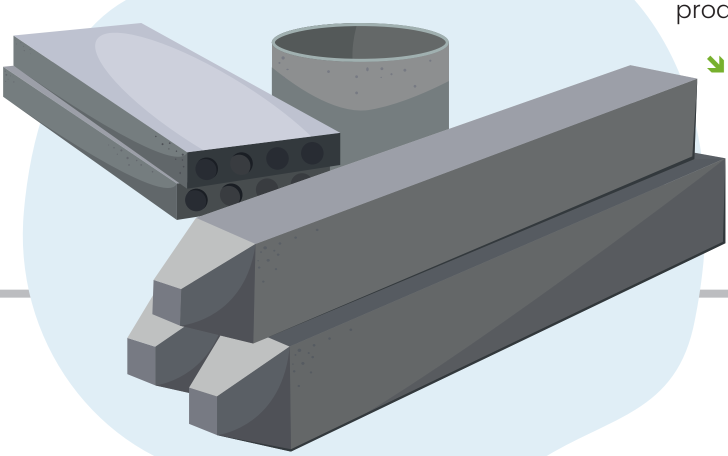
French actors in the development of CO_2 mineralisation technologies are few, and there is no industrial operator or industrial scale pilot or demonstrator in France yet. Due to the local nature of the feedstocks (CO_2, wastes) and associated markets, CO_2 mineralisation appears to be adapted to the scale of SMEs. It is imperative that mineralisation projects be evaluated using a systemic analysis of their economic and environmental benefits for the territory where their deployment is planned. The valorisation of mineralisation co-products (e.g. H2, metals) is an additional lever to fast-track the economic development of CO_2 mineralisation.

Actions

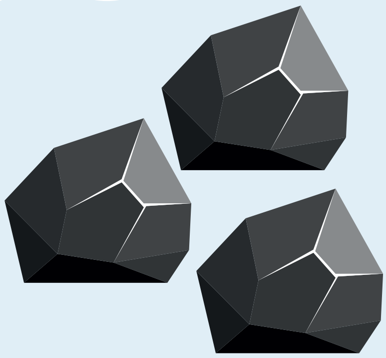
Priority actions to support the development of CO_2 mineralisation processes in France concern all TRL levels, from research to industrial deployment.

Research recommendations

- Enrich thermodynamic and kinetic databases for quantification of the mineralisation potential of carbonatable feedstocks.
- Increase mineralisation kinetics under the most favourable implementation conditions possible (e.g. development of innovative catalytic or biological pathways).
- Develop innovative technologies aimed at the full use of carbonatable feedstocks.
- Explore all possible ways of recovering mineralisation products, for all types of wastes and CO_2 sources (e.g. construction materials, scavenging of toxic metals present in wastes, functionalisation of products, etc.).
- Develop multi-product mineralisation processes (e.g. coupling with production of metal, H2, etc.).
- Integrate CO_2 mineralisation into the eco-design of commercial products.
- Explore the coupling between CO_2 mineralisation and DACC, since DACC is the only capture process capable of producing a controlled CO_2 stream that precisely matches the CO_2 consumption capacity of a given CO_2 utilisation process.



Implementing recommendations



- Mapping CO_2 and carbonatable waste feedstocks on environmental and economic performance criteria specific to the development of mineralisation pathways (development of a GIS dedicated to CO_2 mineralisation).
- Develop methods for quantifying the environmental and economic impact of mineralisation technologies and processes on a territorial scale.
- Develop technologies for integrating mineralisation into industrial production systems.
- Investigate synergies between mineralisation and geological storage of CO_2, where CO_2 and mineralisation mass flows do not match.

Biogenic CO_2 capture and storage in bio-based materials

State of play

Bio-based products and materials are part of the rapidly growing bioeconomy. After harvesting, some of the carbon contained in biomass (agricultural or forestry) can be stored in bio-based products. In order to be a potential carbon sink solution, bio-based products must have a significant lifespan and a high substitution potential (via the replacement of highly emitting fossil-based pathways). These include building materials, transport, sports and leisure components, road materials and pavements, and also packaging, pallet and textiles. A growth in demand or an increase in the lifespan of these products involving additional biomass production can lead to the generation of carbon sinks. At present the main carbon storage pathway in bio-based materials is wood for construction and furnishing in the building sector and to a lesser extent for wood for packaging and paper. In 2016, the total stock of wood products amounted to about 436 Mt CO_2 eq. (CITEPA) and a sink of 1.5 Mt of CO_2 eq. was generated over the year. The "AMS" scenario of the French strategy SNBC provides a decrease in the forest sink in 2050 in favour of wood products, whose annual sink would amount to 21 Mt of CO_2 eq./year, i.e. 25% of all the sink solutions considered.

Nowadays, the major construction companies are involved in the bio-based sector, like Vinci with its subsidiary Arbonis and Bouygues Construction with its WeWood wood construction brand, launched in 2020.

Challenges

There are many ways of developing carbon sinks from bio-based materials, including (i) increasing the market for bio-based products to replace highly emitting fossil energy-based products, while maintaining, or even increasing, the stock of standing biomass, (ii) using other biomass sources that are currently underdeveloped, such as hemp, flax, cork, straw, etc., (iii) extending the lifespan of products through reuse, reworking, recycling, or (iv) adopting less emissive end-of-life solutions such as composting, developing soil construction, combining CO_2 capture and storage to energy production, etc.

The involvement of historical stakeholders and new start-ups is intensifying and the market prospects for several products are already expected to increase, such as concretes and insulators (ADEME, 2021) For the development of these sectors, one of the main challenges is that the French balance of trade in the wood market is currently in deficit, thus the use of a larger harvest requires the development of a more structured French industrial fabric. Furthermore, in order to benefit the climate, it is necessary to ensure good management of the biomass resources mobilised to avoid reducing carbon stock in favour of shorter lifespan pathways. It is also necessary to adapt production systems that have historically relied on fossil or non-biogenic resources. Technological innovations are also expected to develop solutions for the reuse and recycling of these materials. Finally, for all bio-based materials, the management of the end-of-life of products must systematically integrate the avoidance of the emission of the carbon into the atmosphere by identifying and deploying the most suitable solutions to each of the sectors.

Barriers

For the development of bio-based materials market:

MANAGEMENT OF FRENCH FOREST STANDS
not adapted (need to increase softwood sawmill production capacity, promote substitution of softwood timber by hardwood, mobilise more softwood (planting)).

LACK OF ACCEPTABILITY
of some historical stakeholders in the construction industry.

VARIABILITY OF THE QUALITY
and accessibility of wood and of agricultural by-products.

EXTRA-COSTS
for some agricultural biomass (flax, hemp, etc.).

For end-of-life management :

UNDERDEVELOPED TECHNIQUES AND INFRASTRUCTURE
for recycling and not yet operational cost recovery.

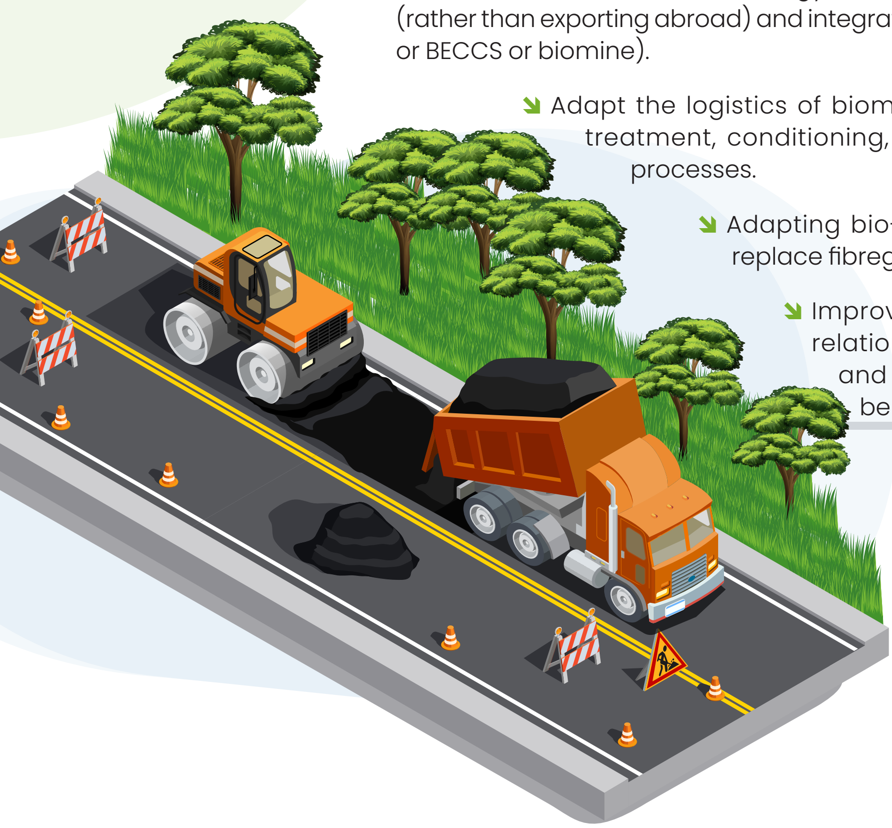
UNDERDEVELOPED ENERGY RECOVERY SYSTEMS
in France (end-of-life products are mainly sent to Belgium).

ORGANIC RECOVERY (COMPOSTING, RETURN TO SOIL)
not proven on many materials (insulation, concrete, etc.).

Actions

Research recommendations

- Rationalise the growth of the wood materials sector in relation to the availability of local resources in compliance with the rules of sustainable forest management.
- Identify, develop and prioritise end-of-life routes for each of the materials towards storage solutions.
- For materials that can have energy recovery, develop the French energy recovery chain (rather than exporting abroad) and integrate into capture and storage systems (composting or BECCS or biomine).
- Adapt the logistics of biomass supply and biomass quality (during pre-treatment, conditioning, storage) to the existing material production processes.
- Adapting bio-based materials to existing uses (e.g. flax to replace fibreglass, hemp for lining car doors, etc.).
- Improve the quantification of substitution effects in relation to the competing sectors, the uses of wood and their future evolution, taking into account the behaviour of consumers and market mechanisms.



Implementing recommendations

- Develop a statistical monitoring of bio-based materials markets and of the origin of feedstocks
- Continue the standardisation/regulation of hardwood products for material use.
- Guiding forestry towards the production of wood quality that meets the criteria of the targeted materials (widening of the range of sizes or qualities admissible in sawmills).
- Further develop the value-added chains of French hardwoods
- Favour the substitution of the most energy-intensive materials and the most GHG-emitting fossil fuels
- Communicate on the climate/sink effect of the bio-based material sectors, whose storage can in some cases be more secure than in forest.
- At the regional level, promote long-life uses of materials from sustainable forest management, in accordance with the incentive to use more wood energy
- Pursue the deployment of material and human resources for recycling and reuse sectors.
- Identify and organize collection routes for organic industrial by-products with a material purpose
- Relocate processing industries in France to enhance local bio-resources
- Increase skills in the "technical wood" sector.

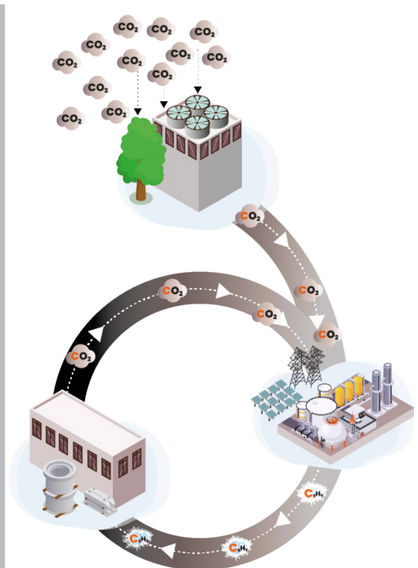
Technological solutions for recycled carbon capture, utilisation, and long-term storage

State of play

From the perspective of a carbon sink analysis, the capture and recycling of CO2 generated by an anthropogenic activity can be classified into different categories, depending on the use:

- mineralisation use. The carbon in CO_2 becomes a constituent of a mineral material and can be stored for the long term. This becomes a carbon sink if CO_2 comes from atmosphere (see worksheet 5)
- successive reuses of atmospheric CO_2, directly or after capture in a bioenergy/bio-refinery unit, or direct conversion of biomass into bio-based materials (whose non-reuse issues are dealt with in worksheets 4 and 5bis)
- closed looping of biogenic or atmospheric industrial concentrated CO_2 in one or more industrial plants.

Closed-loop CO_2 projects are called CCU (Carbon Capture and Utilisation). They currently mobilise concentrated industrial or fossil CO_2 with the aim of achieving carbon neutrality. Then, carbon storage is not what motivates the synthesis of the molecules. They are intended to provide industrial and energy services without depending on primary extraction of fossil resources. Therefore, they allow for the reduction of CO_2 emissions, more than a possible sink. However, some industrial processes and associated products could be capable of producing negative emissions by introducing CO_2 captured from the atmosphere into a closed industrial loop. France has already launched research projects and demonstrators in the fields of fuel production or high added value molecules.



Towards the development of CO2 recovery and reuse for sustainable sequestration

These include JUPITER 1000[1], Methycentre[2], CIMENTALGUE[3], VASCO2[3], HYNOVI[4], REUZE[4], HYNOVERA[4] and HyCaBioMe[5]. Numerous other projects are currently emerging within the framework of programmes supported by ADEME (ZIBAC) in the Dunkirk, Fos-sur-Mer and Le Havre areas, as well as via the Innovation Fund[6] and the IPCEI[7]. French maritime transport is also communicating on a circular carbon economy strategy that effectively considers the use of CO_2 in a closed loop. In this concept, cargo ships could embark capturing devices, in order to capture and store CO_2 emitted by their own stacks, from fuel combustion. The CO_2 resulting from the combustion of these ships' fuels would thus be entirely captured and stored in compressed or liquefied form in the ship which would unload it in the port, to be sent, for example, to a synthetic fuel plant (which could supply these same ships). Through this process, a significant volume of carbon would be sequestered in a closed loop and could generate negative emissions, if CO_2 of biogenic or atmospheric origin is used. The sufficiently long duration (several decades) of this closed cycle remains the indispensable condition for granting the status of sink to these sectors.

1/ JUPITER 1000, a Power to Gas demonstrator with CO2 capture from the chemical industry, supported by GRTgaz
2/ Methycentre, a biogenic CO2 methanation project from biogas, supported by Storengy
3/ CIMENTALGUE and VASCO2, projects for the production of algae from industrial CO2, led respectively by VICAT and the Port of Marseille
4/ HYNOVI, REUZE and HYNOVERA, plants for the production of synthetic fuels from renewable hydrogen and industrial CO2
5/ HyCaBioMe, H2 and CO2 conversion project by biological methanation
6/ Innovation Fund: European funding programme - https://ec. europa. eu/clima/eu-action/funding-climate-action/innovation-fund_en
7/ "Important Projects of Common European Interest" (IPCEI): European mechanism for the promotion of innovation - https://competition-policy. ec. eu- ropa.eu/state-aid/legislation/modernisation/ipcei_en.

Challenges

The characterisation of negative emissions/carbon sinks cannot be dissociated from the period length during which this carbon is removed from the atmosphere, in order to get climate benefits. It is therefore necessary to establish consistency between the sustainability of a carbon sink and the climate mechanisms impacted by the life span of CO_2 in the atmosphere. This point remains difficult to settle because the literature does not show a consensus on a precise duration. A scale of around 100 years has been mentioned, a duration that would allow, a priori, a transition of humanity to carbon neutrality. Should we assume that a sequestration period equivalent to the residence time of a CO_2 molecule in the atmosphere after its emission (order thousands of years) is necessary, in order to affirm that a CO_2 sequestration process in a product can be qualified as a carbon sink operation?

As a matter of fact, the rating of a process or a product containing carbon must take into account the temporal issue and the conditions to be maintained over time to ensure the effectiveness of a carbon sink on the studied scale. If a product has a short life but can be recycled, these conditions are for example:

- the recycling rate is very efficient (close to 100%)
- this recycling is carried out and guaranteed for the minimum duration, estimated necessary to characterise the CO_2 use as a carbon sink.

If 100 years is taken as a reference for the duration of CO_2 sequestration in CCU products, then chemicals, fuels and polymers cannot represent favourable vectors for the generation of carbon sinks except in the case of very efficient and long-lasting recycling.

Hence, this raises questions about the performances of the recycling processes associated with the issues of dispersion or collection of the products. There are few, if any, examples of products currently recycled at rates close to 100% on industrial scales. The steel sector is probably the one that achieves the best process recycling performances but it is still dependent on upstream collection strategies.

Similarly, the condition of guaranteeing the recycling of a product for a period of 100 years is a challenge. It seems difficult to bet that nothing in the next century will break this virtuous process of recycling (economic interest, competing products, major conflict, recovery in a form of partial valorisation neglecting the value of carbon).

The challenge is therefore to:

- identify processes and/or products from CO_2 conversion/upgrading that can generate carbon sinks over sufficient time periods (at least 100 years).
- develop efficient recycling/re-utilisation systems that ensure sustainable use at an affordable quality of service.

Barriers

Apart from mineralisation, no CCU processes currently exists, that allow for permanent CO_2 storage and thus negative emissions. These processes do not constitute carbon sinks, if based on the proposed requirements and the expected service. In addition to the barriers associated with the capture and storage steps mentioned in worksheets 4 and 5, some specific technical barriers can be looked at, such as:

TECHNICO-ECONOMIC BARRIERS
associated with the issues of collection, sorting and recycling (energy consumption, yield), reuse (cleaning, maintenance of product performance), which are also found in the issue of bio-based materials (worksheet 5bis),

INTEGRATION OF CAPTURE DEVICES
and synthesis, in the existing industrial network

MASSIVE ELECTRICITY PRODUCTION
needed for CCU processes (CO_2 capture and conversion using decarbonised hydrogen),

IDENTIFICATION OF INNOVATIVE CAPTURE PROCESSES
of CO_2 in the exhaust, such as that emitted by vehicles with thermal engines, similar to the strategy mentioned by the shipping industry.

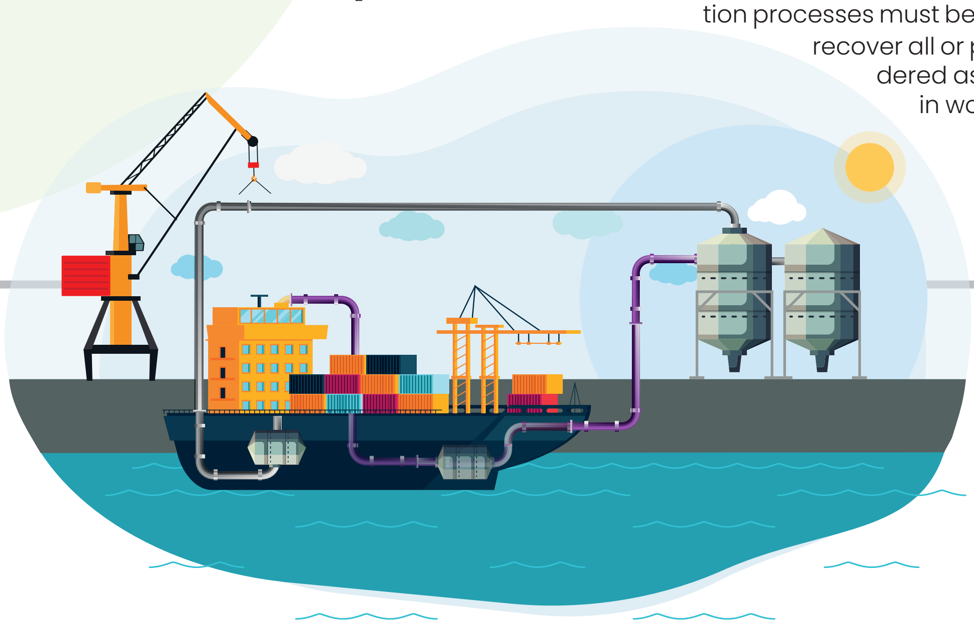
Actions

Before mentioning possible actions, it is important to make some recommendations on how to consider the CCU. These recommendations are part of the accompanying actions.

Implementing recommendations

- Do not systematically link the notion of carbon sinks/negative emissions to CCU processes with storage solution.
- CCU processes to polymer materials, chemical molecules and fuels are mostly dedicated to CO_2 emission reduction or avoidance, based on carbon recycling.

When CO_2 is recycled and valorised in short lifespan products (fuel, chemicals, etc.), the production processes must be combined with other processes to recover all or part of the CO_2 in order to be considered as sink (e.g. BEECS system described in worksheet 4).



In terms of research actions, we can distinguish between avoidance and sink solutions. Therefore, it is important to:

Research recommendations

- Evaluate systems by using multi-criteria analyses, including techno-economic assessment and carbon footprint aspects using 'well to wheel' approaches based on LCA which requires methods developments. The assessments will aim to establish, through balances, the service provided, the gain in terms of emissions and the constraints of these systems (in particular linked to the necessary massive production of decarbonised energy).
- Develop efficient CO_2 capture processes, in order to achieve high recycling rates. While these systems exist for fixed and centralised industrial processes, they must be developed and require specific developments of CO_2 transport and capture pathway for decentralised (residential) or mobile systems.
- Develop efficient CO_2 conversion systems at different scales to produce fuels or materials.
- Develop the interconnection of CO_2 conversion processes with the location of capture processes. This mean developing the transport of CO_2 as a feedstock and thus developing infrastructure (pipes, networks, etc.), for example between the CO_2 unloading area from a boat and the synthetic fuel production infrastructure.

Examples of recommendations for research and governance

Developing carbon flow observatories in natural environments

All terrestrial and aquatic ecosystems are subject to complex bio-geochemical phenomena accompanied by carbon flows in the direction of emissions and absorp- tions that contribute significantly to the level of CO_2 in the atmosphere. In order to limit emissions and increase absorptions, it is necessary to start from detailed observations of these mechanisms in order to improve our understanding and anticipate their effects. This requires significant multidisciplinary advances in the understanding of carbon dynamics in terrestrial eco-systems, the quantification of stocks and flows at different spatio-temporal scales, and the interrelationships of the carbon cycle with other biogeochemical cycles, including that of water, all in a context of global change. The FairCarboN1 exploratory research priority programme and equipment (PEPR) aims to develop the contribution of continental ecosystems to climate change mitigation and carbon neutrality.

Four tracks related to observations of carbon stocks and the processes that affect them have been identified:

1 **Set up coordinated observation services (via INSU, IFREMER, INRAE, BRGM), dedicated to carbon** and distributed among the major research infrastructures (RIs) aimed at observing these environments, such as the Critical Zone Observatories Network (OZCAR), the Coastal and Littoral RI (ILICO), and the future offshore RI. The parameters observed should be linked to instantaneous carbon fluxes (exchange of CO_2 with the atmosphere) but also to perennial sinks (preservation of carbon in coastal sediments and deltas).

2 **Carry out a cartographic inventory of these potential carbon sinks i**n order to estimate the stocks of carbon in these areas and the associated CO2 fluxes: in continental aquatic environments (rivers, lakes, wetlands, mountainous areas), coastal environments (littorals, mudflats, seagrass beds, mangrove swamps, deltas **a**nd continental shelves) and offshore environments (Pacific EEZ).

3 **To study the stability and sensitivity of carbon storage to climatic and environmental parameters** that will be modified during the 21st century. Variations observed in the natural environment over the long term, or during extreme events such as heat waves or intense storms, or those simulated in mesocosms (in the laboratory, in the Ecotron or in situ) could be used to study and model the capacity of ecosystems to store carbon.

4 **Develop and systematise the modelling of physical-chemical-biological processes.** This will allow extrapolation beyond the observed areas, projections for the future (21st century) and the introduction into the models of a better consideration of the crucial ecosystems in carbon storage.

With these tools, support for public policies for sustainable carbon management could be provided on a scientific basis: establishment of protected natural areas around natural carbon sinks (peat bogs, marshes, deltas), and increasing the carbon storage capacity of these areas (extension, transformation by renaturalisation).

1/ PEPR FairCarboN: Launched on 11 April 2022, it has a budget of 40 million euros over 6 years, financed under PIA 4. It is issuing a first call for projects in April to support five targeted projects, in order to federate the French community and increase its international visibility, strengthen interdisciplinary, multi-milieu and multi-actor dialogues: https://anr.fr/PEPR-Explo-FairCarboN-AAP-2022

Example 2

Developing storage methods and practices in more or less anthropised environments

The environments in which management methods or practices for the storage of carbone can be developed include the environments mentioned in sheets 1, 2 and 3 above. Research activities related to carbon storage in anthropised environments are divided into four areas: measuring the potential, optimising storage practices based on quantitative storage measurements, raising the awareness of stakeholders and anticipating the evolution of impacts related to the effects of climate change.

1 While agricultural and forest soils already benefit from regular inventories, urban and periurban environments cover a wide variety of land use and management, which is not systematically monitored. A first challenge would be to list and measure the areas likely to store carbon. **A cartographic inventory** requires the mobilisation of all land-use planning stakeholders and the setting up of observatories.

2 Quantifying the impact of current practices in terms of carbon storage requires the implementation of evaluation systems based on **quantitative balances** according to climatic and agronomic conditions. Following the example of the 4/1000 initiative (INRAE, 2019) carried out for the agricultural sector, similar initiatives can be carried out in forestry and urban environments. A comparison between urban and agricultural contexts in terms of practices and impact on carbon storage and their evolution can also be carried out. These data will allow the **optimisation of storage practices** according to the anthropised surfaces concerned, by integrating all the associated ecosystem services (biodiversity, heat island, air quality, etc.). It should be noted that the quantification of potential carbon storage in soils cannot be dissociated from the quantification of nitrogen in order to be able to assess the long-term effects of this storage.

3 Based on the assessment of the areas that can be used to store carbon, the various **stakeholders involved in the management and use of these areas must be made aware of the** need to take into consideration carbon storage and the avoidance of release in the management of the various areas. These actors are very diverse, with local authorities, road, rail and airport operators at the forefront. The deployment of the Low Carbon Label methodologies contributes to this process of involving local players.

4 Once the stocking practices have been determined in a given pedoclimatic context, it is necessary to feed the models that allow **the possible impacts of climate change** on these practices to be **anticipated,** as well as to measure the impacts of these practices on limiting climate change.

Example 3

Worksheet 4

Deepen knowledge on national geological reservoirs

A recent report by ADEME (ADEME, 2020) proposes a mapping of the different geological storage sites for CO2 in France and an analysis of their storage challenges and potential. Beyond the identification of storage sites, there is a significant need for further work on the **control of the various reservoir characteristics.** These characteristics include the porosity of the rocks, their thickness, and their permeability, in particular with a view to measuring the tightness of the reservoirs. The stability of the environment must also be taken into account. It is also necessary to anticipate the tolerance of the reservoirs to the constituent compounds of the sequestered gases. This knowledge would allow to determine on a case-by-case basis the level of gas purification required by the reservoir before sequestration.

The evaluation of reservoir **storage capacities** also needs to be clarified. According to the ADEME report, work is underway to develop new methods for calculating storage capacity using dynamic modelling that integrates several parameters that could potentially reduce the available space (reservoir pressure, migration of the CO2 cloud during injection).

In addition to the study of CO2 gas storage reservoirs, French territories could also have **solid carbon storage reservoirs or Biomines.** Among them, former coal mines or quarries could be used for temporary or long-term storage of solid biogenic carbon such as biochar or other by-products of the bioeconomy. This type of storage is currently being considered. Firstly, an **inventory of potential** storage **sites** for this form of carbon could be carried out in France. Studies on the mechanical and chemical stability of biochar are already underway, with a view to an agronomic use by spreading on agricultural soils. With prospects for storage in cavities, further research on the **densification of these biochars** into "carbon ingots" or "carbon loaves" could also be relevant in order to increase their volume and stability.

Example 4

Worksheets 4 et 6

Develop national demo projects for negative emissions technologies

Among the technological sink solutions, worksheet 4 cites the capture and storage of biogenic CO_2 emitted by bioenergy production plants (BECCS). This solution has been under study for many years, and the technical issues associated with capture and storage are similar to those of the industrial plants envisaged for the deployment of CCS in general. Although in some contexts, their capacity to generate negative emissions has been demonstrated, only a few countries currently have industrial-scale facilities (USA, Canada, Japan, Norway, and United Kingdom). France has many bioenergy installations that co-produce capturable CO_2 (wood heat, wood cogeneration, methanisation plants, ethanol plants, etc.) It also has a significant potential for the deployment of new energies from biomass, and has potentially close and accessible geological reservoirs. Industrial charcoal production facilities could also be demonstration sites for biorefineries with biochar storage. However, no BECCS demo project has been announced in France to date.

These demonstration projects would aim at scaling up and integrating renewable energies or decarbonised energy sources with CO_2 capture and process technologies in order to reduce costs, increase energy, increase environmental efficiency, and make the systems duplicable.

In particular, they could enable to:

- assess the feasibility of modular capture/treatment systems at low CO_2 emitting sites capacity (methanisation, biomass combustion, etc.),
- identify the most suitable means of transport if a storage site is not nearby,
- determine the volumes and caves for which CO_2 capture and transport modules are economically feasible and viable,
- identify the most suitable locations for industrial sites (proximate to biomass resources, bioenergy uses or CO_2 storage etc.),
- ensure the carbon sink function of the entire system by integrating all stored and emitted carbon streams, based on actual data, throughout the process.

Example 5

Worksheet 5

An expert GIS for the deployment of CO_2 mineralisation

Bringing alkaline waste (e.g. bottom ash, fly ash) into contact with CO2 can make it possible to produce materials (e.g. aggregates, supplementary cementitious materials) in high demand, in large quantities, for the construction sector in particular. Also called mineralisation, this solution for using CO2 is both a vector of decarbonisation and circularization of the economy. Due to the geographical location of the waste and CO2 feedstocks, but also of the markets that can absorb mineralisation products, the development of mineralisation value-added chains and mineralisation technologies requires a strong territorial anchorage.

To support the deployment of economic sectors and the development of innovative and efficient CO2 mineralisation technologies, the setting up of a national Expert Geographic Information System (EXGIS) dedicated to CO2 mineralisation is recommended. On a grid that covers the whole country, such an information system will provide access to all the key information for designing and costing technological mineralisation sectors on any given region. In particular, the data will include all the mineralisation information, over short to long time horizons, the quantity and quality of existing or potential alkaline feedstocks and CO2 emitters, as well as the characteristics of the markets likely to sell mineralisation products.

The expert system that will be coupled with the GIS will provide a prospective and regionalized costing of possible mineralisation pathways in environmental, economic and technological terms. Such a system would be used to identify and define potential value chains, to support entrepreneurial initiatives and demonstration projects necessary to test mineralisation on a large scale, and to guide the development of innovative mineralisation technologies.

Example 6

Worksheets 1, 2, 3, 4, 5, 5bis and 6

Improvement and harmonisation of environmental assessment methods for negative emissions solutions

Life Cycle Assessment (LCA) is a standardised environmental assessment method for calculating different types of impacts associated with a product, production system or service, taking into account all stages of the life cycle of products and services, from the origin of the resources used to the end of life of the products and services. This type of analysis is commonly used to assess the impacts of energy transition sectors on climate change. This type of approach, which considers all the processes involved in the sectors, seems necessary to support the development of negative emissions solutions in order to justify the negative carbon balance of the system under consideration. It is also necessary to compare the environmental performance of different systems on climate change but also in other impact categories such as land use. To carry out these assessments, the development of methodological guidelines, in support of the existing normative framework for LCA, is still necessary. This will enable practices to be harmonised and a fair comparison to be made between integrated systems of very different natures (i.e. agricultural production systems with soil rendering vs. energy production technologies with CCS) and aiming to achieve several differentiated objectives (reduction of CO2 in the atmosphere but also energy production, supply of materials, etc.). It is also necessary to improve LCA tools with a view to integrating the temporal dimension into the inventory (particularly with a view to integrating technological developments within the systems) and during the characterisation of impacts (temporal distribution of CO2 emission and capture phases). Finally, the enrichment or creation of shared and harmonised inventory databases, for example via thematic modules, would allow greater robustness of results and facilitate the integration of new data from current and future R&I projects. In these three areas of development, collaborative work between institutes and the pooling of methods, and data, and results is essential. This calls for the deployment of open multi-partner projects benefiting from a centralisation of the capitalisation and dissemination of results.

Example 7

Recommendations for support and governance actions

All the families of solutions have highlighted the need for support and governance actions that can be summarised here in three main actions.

- The first would be to set up **groups of players** (inter-professional, federation, association, etc.) from various backgrounds (industrialists, local authorities, researchers, citizens, etc.) with the aim to **pooling the means for** identifying natural sinks and extending the deployment of storage practices. In addition, such groupings would help to identify the position of the various stakeholders along the value chain, to identify the expected business models and the distribution of economic and environmental costs and benefits.

- **Disseminating information** on the benefits and risks associated with different carbon sink solutions to the general public, policy makers and NGOs, could also play a major role of this type of grouping. Important communication needs include (i) the levels of risk associated with geological storage of CO_2 , (ii) the levels of risk associated with the rehabilitation of polluted soils, and (iii) the virtuous management and use of wood in forests.

- Finally, given the potential convergence of solutions between neighbouring countries, particularly with regard to storage conditions in natural environments and access to potential shared geological reservoirs, actions **to coordinate international research and regulations** appear necessary. Networks such as ECCSEL (European Research Infrastructure for CO_2 Capture, Utilisation, Transport and Storage) could be expanded. Regulations on the sustainability of biomass mobilisation for energy, materials and other storage purposes could be standardised. The same could be done for the deployment and management of CO_2 transport and storageinfrastructures .

In general terms, specific public funds and support programmes (national and multi-national) will have to be deployed for the implementation of each of these solutions

Acronyms

ADEME: Agence De l'Ecologie et de la Maitrise de l'Energie (The French Agency for Ecological Transition)
LCA: Life Cycle Assessment
AMS: Avec Mesures Supplémentaires (With Supplementary Measures)
BECCS: BioEnergy with Carbon Capture and Storage
BRGM: Bureau de Recherches Géologiques et Minières
BO: Bois d'Oeuvre (Timber)
BTP: Batiment et Travaux Publics (Building and Public Works)
CCU: Carbon Capture and Utilisation
CCUS: Carbon, Capture, Utilisation and Storage
CCS: Carbon, Capture and Storage
CITEPA: Centre interprofessionnel technique d'études de la pollution atmosphérique (Interprofessional Technical Centre for Air Pollution Studies)
CEA: Commissariat à l'Energie Atomique et aux Energies Alternatives (The French Atomic Energy and Alternative Energy Commission)
CNRS: Centre National de la Recherche Scientifique (National Center for Scientific Research)
CSTB: Centre Scientifique et Technique du Bâtiment (French Scientific and Technical Centre for Building)
DAC: Direct Air capture
DACCS: Direct Air Carbon Capture and Storage
ECCSEL: European Research Infrastructure for CO_2 Capture, Utilisation, Transport and Storage
EFESE: Evaluation Française des Ecosystèmes et des Services Ecosystémiques (French Evaluation of Ecosystems and Ecosystem Services)
EIFER: European Institute for Energy Research
ENSIACET: École Nationale Supérieure des Ingénieurs en Arts Chimiques et Technologiques (Toulouse INP-ENSIACET Graduate Engineering school)
EPF: Etablissement Public Foncier (Public Land Agency)
GEPEA: GEnie des Procédés Environnement - Agroalimentaire (Environmental Process Engineering - Food Industry)
GHG: Greenhouse Gases
ICBMS: Institut de Chimie et de Biochimie Moléculaires et Supramoléculaires (Institute of Molecular and Supramolecular Chemistry and Biochemistry)
IFREMER: Institut Français de Recherche pour l'Exploitation de la Mer (National Institute for Ocean Science)
IFPEN: IFP Energies Nouvelles (IFP New Energies)
INP: Institut National Polytechnique (National Polytechnique Institute)
INRAE: Institut national de recherche pour l'agriculture l'alimentation et l'environnement (National Research Institute for Agriculture, Food and the Environment)
IPSL: Institut Pierre Simon Laplace
LIEC: Laboratoire Interdisciplinaire des Environnements Continentaux (Interdisciplinary Laboratory of Continental Environments)
LRGP: Laboratoire Réactions et Génie des Procédés (Reactions and Process Engineering Laboratory)
LSCE: Laboratoire des Sciences du Climat et de l'Environnement (Laboratory of Climate and Environmental Sciences)
OM: Organic Matter
Mt: Millions of tonnes
MTES: Ministère de la Transition Ecologique et Solidaire (French Ministry of Ecological and Social Transition)
PCC: Precipitated Calcium Carbonate
PIA: Programme d'Investissements d'Avenir (Investment Programme for the Future)
SME: Small and Medium Enterprise
REFIOM: Résidus d'Épuration des Fumées d'Incinération des Ordures Ménagères (Residues from the treatment of waste incineration fumes from household waste)
SNBC: Stratégie Nationale Bas Carbone (National Low Carbon Strategy)
TRL: Technical Readiness Level
UL: University of Lorraine
EEZ: Exclusive Economic Zone

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